

LIMNOLOGICAL CHARACTERISTICS OF
NORTHERN LAKE MICHIGAN, 1976

Part 1. Physical-chemical Conditions

by

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and

Part 2. Phytoplankton Population Studies

by

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RECOMMENDATIONS

The importance of obtaining seasonal data on Lake Michigan for major or even relatively small areas of the basin is apparent to anyone who has attempted to use historical data either for scientific or management purposes. Unfortunately, data that could be used to answer questions that are raised about nutrient enrichment and eutrophication are not available in the historical data base. Even more unfortunately, there is presently no systematic effort to correct this situation for future researchers and managers. No lake-wide or seasonal studies have been conducted since 1976-1977 when the present study and the one by Rockwell et al. (1980) were undertaken. It is therefore important to initiate a series of studies on Lake Michigan that would correct this deficiency and fulfill the needs listed below.

For convenience of presentation, recommendations have been listed under three headings: ecosystem studies and processes, assessment of long-term changes, and special problem areas. However, open-lake studies on long-term changes and ecosystem processes cannot be separated completely because data from one type of study can be transferred to another. In contrast, studies related to special problem areas may be more specific and may not have specific applicability to the entire lake basin.

ECOSYSTEM STUDIES AND PROCESSES

Although the present study was designed to provide data related to problems of eutrophication and nutrient enrichment, it should be realized that these data will also be useful in assessing ecosystem changes that result from

other types of anthropogenic inputs. Future programs should be directed to comprehensive studies of ecosystem functions and processes as well as to obtaining descriptive data on environmental properties.

Effort should be directed to studies of seasonal changes in physical-chemical conditions and how they are related to species composition and dynamics of phytoplankton and zooplankton. Such a study could be undertaken in conjunction with the study of seasonal and spatial changes in total phosphorus.

A study should be undertaken to determine the sources of variability in sampling total phosphorus concentrations in the lake. This study should be designed to determine whether seasonal and depth differences in total phosphorus concentrations are present.

Studies on the dynamics of phosphorus in the system should be undertaken. Rates of recycling and losses and how they are affected by different ecosystem processes are important because the absolute concentration of total phosphorus in the water is not large, approximately 8 $\mu\text{g P/liter}$ on an average basis. Only small reductions in absolute concentrations can be expected as the result of different phosphorus control strategies because Lake Huron and Lake Superior, the most oligotrophic of the Laurentian Great Lakes, have average total phosphorus concentrations of 5 and 4 $\mu\text{g P/liter}$.

ASSESSMENT OF LONG-TERM CHANGES

One of the greatest long-term record needs is for additional data on species composition and abundance of phytoplankton. The scant historical record shows that phytoplankton communities have changed drastically. It is likely that several series of species dominances and subsequent replacement by

other species have occurred in the lake in the last 30 to 60 years. No other indicator of environmental change offers this degree of sensitivity nor number of entities (species) that can be related to change. Studies of phytoplankton are needed on an annual basis so year-to-year variability can be separated from long-term changes in water quality.

Studies on other biological components of the system can increase our understanding of system dynamics and aid in assessing long-term changes in water quality. However, it is not likely that changes in water quality can be as readily related to zooplankton species composition and abundance as can be done for phytoplankton species composition and abundance. The same can be stated for benthos. Relatively few long-term studies of benthos and zooplankton have been undertaken, and historical changes in species composition of either benthos or zooplankton have not been as drastic as those for phytoplankton. There has been no lake-wide disappearance of dominant benthic organisms, for example.

Data should be obtained on long-term changes in different chemical constituents of lake waters. For many of the variables of interest, particularly nutrients, data can be obtained at relatively little cost in conjunction with studies of seasonal dynamics. Data must be obtained over a large enough geographic area to be representative of lake-wide conditions. Sample strategies must be based on seasonal dynamics of the variables of interest. Data on chloride, for example, can be collected relatively infrequently because of its conservative behavior; whereas, much more sampling is necessary to assess long-term changes in nutrients. Data are also needed to assess long-term changes in trace metals and toxic organics. Analytical

costs to obtain these data dictate that sampling efforts should be optimized to yield the greatest amount of information at a reasonable cost.

SPECIAL PROBLEM AREAS

Assessing changes in the open lake is a separate and distinct problem compared to evaluating changes in smaller portions of the lake basin. There are three distinct special problem areas that should be considered separately from open-lake assessment. The three areas are: 1) the nearshore zone in general, but especially near large anthropogenic nearshore loadings; 2) Green Bay and the area influenced by exchange of water between the bay and open lake; and 3) the Straits of Mackinac and the area influenced by exchange of water between Lake Michigan and Lake Huron. Each of these areas has unique features and problems that should be investigated. Studies of impacted nearshore areas would be most critical in the future because processes in these areas affect the input of pollutants to the offshore portions of the lake.

These recommendations have been formulated in relation to problems related to nutrient enrichment and eutrophication. However, they also are important in addressing questions that are related to basic understanding of system processes and if implemented would provide useful information related to problems other than eutrophication.

CONTENTS

| | |
|--|------|
| Acknowledgment..... | ii |
| Recommendations..... | iii |
| Ecosystem Studies and Processes..... | iii |
| Assessment of Long-Term Changes..... | iv |
| Special Problem Areas..... | vi |
| Figures..... | viii |
| Tables..... | xiv |
| PART 1..... | 1 |
| Introduction..... | 2 |
| Station Selection..... | 4 |
| Discussion..... | 7 |
| Methods..... | 10 |
| Spatial Distribution..... | 16 |
| Cruise 1, 22-28 April..... | 16 |
| Cruise 2, 2-7 June..... | 29 |
| Cruise 3, 10-17 July..... | 41 |
| Cruise 4, 12-17 August..... | 53 |
| Cruise 5, 7-13 October..... | 65 |
| Seasonal Changes..... | 76 |
| Water Temperature..... | 76 |
| Hydrogen Ion Concentration..... | 79 |
| Nitrate Nitrogen..... | 82 |
| Soluble Reactive Silica..... | 88 |
| Particulate Silica..... | 92 |
| Chlorophyll <u>a</u> | 95 |
| Total Phosphorus..... | 99 |
| Total Soluble Phosphorus..... | 102 |
| Ammonia Nitrogen..... | 102 |
| Chloride..... | 106 |
| Straits of Mackinac..... | 108 |
| Water Temperature..... | 108 |
| Hydrogen Ion Concentration..... | 110 |
| Nitrate Nitrogen..... | 110 |
| Ammonia Nitrogen..... | 111 |
| Soluble Reactive Silica..... | 111 |
| Particulate Silica..... | 112 |
| Chlorophyll <u>a</u> | 113 |
| Total Phosphorus..... | 113 |
| Total Soluble Phosphorus..... | 114 |
| Chloride..... | 114 |
| References..... | 124 |
| PART 2..... | 127 |
| Introduction..... | 128 |
| Materials and Methods..... | 128 |
| Phytoplankton Distribution in Near Surface Waters..... | 129 |
| Vertical Phytoplankton Distribution..... | 186 |
| Discussion and Conclusions..... | 227 |
| References..... | 233 |
| Appendix 1. Phytoplankton Species Abundance..... | 235 |

FIGURES

| | Page |
|--|------|
| FIG. 1. Map of stations in northern Lake Michigan sampled in 1976 by the Great Lakes Research Division, University of Michigan, as part of a study sponsored by the Environmental Protection Agency. | 6 |
| FIG. 2. Flow chart illustrating sample processing for study of water samples from northern Lake Michigan. | 12 |
| FIG. 3. Water temperature ($^{\circ}\text{C}$) on Cruise 1, 22-28 April 1976. . . . | 17 |
| FIG. 4. Hydrogen ion concentration (pH) on Cruise 1, 22-28 April 1976. | 19 |
| FIG. 5. Nitrate nitrogen ($\text{mg NO}_3\text{-N/liter}$) on Cruise 1, 22-28 April 1976. | 20 |
| FIG. 6. Soluble reactive silica ($\text{mg SiO}_2\text{/liter}$) on Cruise 1, 22-28 April 1976. | 23 |
| FIG. 7. Particulate silica ($\text{mg SiO}_2\text{/liter}$) on Cruise 1, 22-28 April 1976. | 24 |
| FIG. 8. Chlorophyll <u>a</u> ($\mu\text{g/liter}$) on Cruise 1, 22-28 April 1976. . . | 26 |
| FIG. 9. Water temperature ($^{\circ}\text{C}$) on Cruise 2, 2-7 June 1976. | 30 |
| FIG. 10. Hydrogen ion concentration (pH) on Cruise 2, 2-7 June 1976. | 31 |
| FIG. 11. Nitrate nitrogen ($\text{mg NO}_3\text{-N/liter}$) on Cruise 2, 2-7 June 1976. | 33 |
| FIG. 12. Soluble reactive silica ($\text{mg SiO}_2\text{/liter}$) on Cruise 2, 2-7 June 1976. | 34 |
| FIG. 13. Particulate silica ($\text{mg SiO}_2\text{/liter}$) on Cruise 2, 2-7 June 1976. | 37 |
| FIG. 14. Chlorophyll <u>a</u> ($\mu\text{g/liter}$) on Cruise 2, 2-7 June 1976. . . . | 38 |
| FIG. 15. Water temperature ($^{\circ}\text{C}$) on Cruise 3, 10-17 July 1976. . . . | 42 |
| FIG. 16. Hydrogen ion concentration (pH) on Cruise 3, 10-17 July 1976. | 44 |
| FIG. 17. Nitrate nitrogen ($\text{mg NO}_3\text{-N/liter}$) on Cruise 3, 10-17 July 1976. | 45 |

| | | |
|----------|--|----|
| FIG. 18. | Soluble reactive silica (mg SiO ₂ /liter) on Cruise 3, 10-17 July 1976. | 47 |
| FIG. 19. | Particulate silica (mg SiO ₂ /liter) on Cruise 3, 10-17 July 1976. | 49 |
| FIG. 20. | Chlorophyll <u>a</u> (μg/liter) on Cruise 3, 10-17 July 1976. . . | 50 |
| FIG. 21. | Water temperature (°C) on Cruise 4, 12-17 August 1976. . . . | 54 |
| FIG. 22. | Hydrogen ion concentration (pH) on Cruise 4, 12-17 August 1976. | 56 |
| FIG. 23. | Nitrate nitrogen (mg NO ₃ -N/liter) on Cruise 4, 12-17 August 1976. | 57 |
| FIG. 24. | Soluble reactive silica (mg SiO ₂ /liter) on Cruise 4, 12-17 August 1976. | 59 |
| FIG. 25. | Particulate silica (mg SiO ₂ /liter) on Cruise 4, 12-17 August 1976. | 61 |
| FIG. 26. | Chlorophyll <u>a</u> (μg/liter) on Cruise 4, 12-17 August 1976. . | 62 |
| FIG. 27. | Water temperature (°C) on Cruise 5, 7-13 October 1976. . . | 66 |
| FIG. 28. | Hydrogen ion concentration (pH) on Cruise 5, 7-13 October 1976. | 67 |
| FIG. 29. | Nitrate nitrogen (mg NO ₃ -N/liter) on Cruise 5, 7-13 October 1976. | 69 |
| FIG. 30. | Soluble reactive silica (mg SiO ₂ /liter) on Cruise 5, 7-13 October 1976. | 71 |
| FIG. 31. | Particulate silica (mg SiO ₂ /liter) on Cruise 5, 7-13 October 1976. | 72 |
| FIG. 32. | Chlorophyll <u>a</u> (μg/liter) on Cruise 5, 7-13 October 1976. . | 74 |
| FIG. 33. | Seasonal changes in water temperature at master stations. . | 77 |
| FIG. 34. | Seasonal changes in pH at master stations. | 81 |
| FIG. 35. | Seasonal changes in nitrate nitrogen at master stations. . | 84 |
| FIG. 36. | Seasonal changes in soluble reactive silica at master stations. | 89 |
| FIG. 37. | Seasonal changes in particulate silica at master stations. | 93 |

| | | |
|----------|--|-----|
| FIG. 38. | Seasonal changes in chlorophyll <u>a</u> at master stations. . . . | 96 |
| FIG. 39. | Seasonal changes in total phosphorus at master stations. . | 100 |
| FIG. 40. | Seasonal changes in ammonia nitrogen at master stations. . | 105 |
| FIG. 41. | Hypsographic curve of Lake Michigan as cumulative percent of area and volume (from Long and Schueler 1968). | 118 |
| FIG. 42. | Seasonal distribution and abundance trends of the total phytoplankton assemblage (cells/mL). | 130 |
| FIG. 43. | Seasonal distribution and abundance trends of diatoms. . . | 132 |
| FIG. 44. | Seasonal distribution of the genus <u>Achnanthes</u> | 133 |
| FIG. 45. | Seasonal distribution of the genus <u>Amphora</u> | 134 |
| FIG. 46. | Seasonal distribution of <u>Asterionella formosa</u> | 136 |
| FIG. 47. | Seasonal distribution of <u>Cyclotella comensis</u> | 137 |
| FIG. 48. | Seasonal distribution of <u>Cyclotella comta</u> | 138 |
| FIG. 49. | Seasonal distribution of <u>Cyclotella ocellata</u> | 140 |
| FIG. 50. | Seasonal distribution of <u>Cyclotella pseudostelligera</u> | 141 |
| FIG. 51. | Seasonal distribution of <u>Cyclotella stelligera</u> | 142 |
| FIG. 52. | Seasonal distribution of the genus <u>Cymbella</u> | 143 |
| FIG. 53. | Seasonal distribution of <u>Diatoma tenue</u> var. <u>elongatum</u> . . . | 145 |
| FIG. 54. | Seasonal distribution of <u>Fragilaria crotonensis</u> | 146 |
| FIG. 55. | Seasonal distribution of <u>Fragilaria pinnata</u> | 147 |
| FIG. 56. | Seasonal distribution of <u>Melosira islandica</u> | 149 |
| FIG. 57. | Seasonal distribution of <u>Melosira italica</u> subsp. <u>subarctica</u> | 150 |
| FIG. 58. | Seasonal distribution of the genus <u>Navicula</u> | 151 |
| FIG. 59. | Seasonal distribution of <u>Rhizosolenia eriensis</u> | 152 |
| FIG. 60. | Seasonal distribution of <u>Rhizosolenia gracilis</u> | 154 |
| FIG. 61. | Seasonal distribution of <u>Stephanodiscus hantzschii</u> | 155 |

| | | |
|----------|---|-----|
| FIG. 62. | Seasonal distribution of <u>Stephanodiscus minutus</u> | 157 |
| FIG. 63. | Seasonal distribution of <u>Stephanodiscus subtilis</u> | 158 |
| FIG. 64. | Seasonal distribution of <u>Synedra filiformis</u> | 159 |
| FIG. 65. | Seasonal distribution of <u>Synedra delicatissima</u> var. <u>angustissima</u> | 160 |
| FIG. 66. | Seasonal distribution of <u>Synedra ostenfeldii</u> | 162 |
| FIG. 67. | Seasonal distribution of <u>Tabellaria flocculosa</u> var. <u>linearis</u> | 163 |
| FIG. 68. | Seasonal distribution and abundance trends of green algae. | 164 |
| FIG. 69. | Seasonal distribution of <u>Ankistrodesmus falcatus</u> | 166 |
| FIG. 70. | Seasonal distribution of <u>Ankistrodesmus</u> (sp. #6). | 167 |
| FIG. 71. | Seasonal distribution of <u>Gloeocystis planctonica</u> | 168 |
| FIG. 72. | Seasonal distribution of <u>Nephrocytium agardhianum</u> | 169 |
| FIG. 73. | Seasonal distribution of <u>Scenedesmus bicellularis</u> | 171 |
| FIG. 74. | Seasonal distribution and abundance of chrysophytes. | 172 |
| FIG. 75. | Seasonal distribution of the genus <u>Dinobryon</u> | 174 |
| FIG. 76. | Seasonal distribution of the genus <u>Ochromonas</u> | 175 |
| FIG. 77. | Seasonal distribution and abundance of blue-green algae (cells/mL). | 176 |
| FIG. 78. | Seasonal distribution of <u>Anabaena flos-aquae</u> | 177 |
| FIG. 79. | Seasonal distribution of <u>Anacystis incerta</u> | 178 |
| FIG. 80. | Seasonal distribution of <u>Anacystis thermalis</u> | 180 |
| FIG. 81. | Seasonal distribution of <u>Schizothrix calcicola</u> (filaments/ mL). | 181 |
| FIG. 82. | Seasonal distribution of and abundance of cryptomonads (cells/mL). | 182 |
| FIG. 83. | Seasonal distribution and abundance of dinoflagellates (cells/mL). | 184 |

| | | |
|-----------|---|-----|
| FIG. 84. | Seasonal distribution and abundance of unidentified flagellates (cells/mL). | 185 |
| FIG. 85. | Vertical distribution of total phytoplankton abundance. . . | 187 |
| FIG. 86. | Vertical distribution of diatoms. | 189 |
| FIG. 87. | Vertical distribution of <u>Asterionella formosa</u> | 190 |
| FIG. 88. | Vertical distribution of <u>Cyclotella comensis</u> | 191 |
| FIG. 89. | Vertical distribution of <u>Cyclotella comta</u> | 192 |
| FIG. 90. | Vertical distribution of <u>Cyclotella ocellata</u> | 193 |
| FIG. 91. | Vertical distribution of <u>Cyclotella stelligera</u> | 194 |
| FIG. 92. | Vertical distribution of <u>Diatoma tenue</u> var. <u>elongatum</u> . . . | 196 |
| FIG. 93. | Vertical distribution of <u>Melosira islandica</u> | 197 |
| FIG. 94. | Vertical distribution of <u>Melosira italica</u> subsp. <u>subarctica</u> | 198 |
| FIG. 95. | Vertical distribution of <u>Rhizosolenia eriensis</u> | 199 |
| FIG. 96. | Vertical distribution of <u>Rhizosolenia gracilis</u> | 200 |
| FIG. 97. | Vertical distribution of <u>Stephanodiscus hantzschii</u> | 201 |
| FIG. 98. | Vertical distribution of <u>Stephanodiscus minutus</u> | 202 |
| FIG. 99. | Vertical distribution of <u>Synedra filiformis</u> | 204 |
| FIG. 100. | Vertical distribution of <u>Synedra delicatissima</u> var. <u>angustissima</u> | 205 |
| FIG. 101. | Vertical distribution of <u>Synedra ostenfeldii</u> | 206 |
| FIG. 102. | Vertical distribution of <u>Tabellaria flocculosa</u> var. <u>linearis</u> | 207 |
| FIG. 103. | Vertical distribution of green algae. | 208 |
| FIG. 104. | Vertical distribution of green filament sp. #5. | 209 |
| FIG. 105. | Vertical distribution of <u>Ankistrodesmus falcatus</u> | 211 |
| FIG. 106. | Vertical distribution of <u>Scenedesmus bicellularis</u> | 212 |
| FIG. 107. | Vertical distribution of <u>Ankistrodesmus</u> sp. #6. | 213 |

| | | |
|-----------|---|-----|
| FIG. 108. | Vertical distribution of blue-green algae. | 214 |
| FIG. 109. | Vertical distribution of <u>Anacystis incerta</u> | 215 |
| FIG. 110. | Vertical distribution of <u>Anacystis thermalis</u> | 216 |
| FIG. 111. | Vertical distribution of <u>Schizothrix calcicola</u> (filaments/ mL). | 217 |
| FIG. 112. | Vertical distribution of chrysophytes. | 218 |
| FIG. 113. | Vertical distribution of the genus <u>Ochromonas</u> | 219 |
| FIG. 114. | Vertical distribution of cryptomonads. | 220 |
| FIG. 115. | Vertical distribution of the genus <u>Cryptomonas</u> | 221 |
| FIG. 116. | Vertical distribution of <u>Rhodomonas minuta</u> | 222 |
| FIG. 117. | Vertical distribution of <u>Rhodomonas minuta</u> var. <u>nannoplanctica</u> | 223 |
| FIG. 118. | Vertical distribution of dinoflagellates. | 225 |
| FIG. 119. | Vertical distribution of unidentified flagellates. | 226 |

TABLES

| | | |
|-----------|---|-----|
| TABLE 1. | Locations and depths of stations sampled in northern Lake Michigan during 1976..... | 8 |
| TABLE 2. | Seasonal changes in average water temperature (°C) for depth strata in offshore and nearshore waters..... | 78 |
| TABLE 3. | Seasonal changes in average hydrogen ion concentration (pH) for depth strata in offshore and nearshore waters..... | 83 |
| TABLE 4. | Seasonal changes in average nitrate-nitrogen (µg N/liter) for depth strata in offshore and nearshore waters..... | 85 |
| TABLE 5. | Seasonal changes in average soluble reactive silica (mg SiO ₂ /liter) for depth strata in offshore and nearshore waters..... | 90 |
| TABLE 6. | Seasonal changes in average particulate silica (mg SiO ₂ /liter) for depth strata in offshore and nearshore waters..... | 94 |
| TABLE 7. | Seasonal changes in average chlorophyll <u>a</u> (µg/liter) for depth strata in offshore and nearshore waters..... | 98 |
| TABLE 8. | Seasonal changes in average total phosphorus (µg/liter) for depth strata in offshore and nearshore waters..... | 101 |
| TABLE 9. | Seasonal changes in average total soluble phosphorus (µg P/liter) for depth strata in offshore and nearshore waters..... | 103 |
| TABLE 10. | Seasonal changes in average ammonia concentrations (µg/liter) for depth strata in offshore and nearshore waters..... | 104 |
| TABLE 11. | Seasonal changes in average chloride concentrations (mg/liter) for depth strata in offshore and nearshore waters..... | 107 |
| TABLE 12. | Average concentrations for 5-m samples from the Straits of Mackinac stations..... | 109 |
| TABLE 13. | Representative values for physical-chemical variables in offshore and nearshore waters of Lake Michigan..... | 120 |
| TABLE 14. | Maximum total phosphorus and chlorophyll <u>a</u> concentrations and seasonal changes in silica and nitrate nitrogen concentrations in the Great Lakes..... | 121 |

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Part 1. Physical-chemical Conditions

by

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INTRODUCTION

Lake Michigan is probably the most interesting of the upper Great Lakes as a subject for study of nutrient enrichment effects on phytoplankton. It is the most eutrophic of the three upper Great Lakes, but few of the classical characteristics of eutrophic environments have been reported from the lake. In the main lake the extent of oxygen depletion is small (Ayers et al. 1967), and gross changes in plankton and benthos, of the type recorded for Lake Erie, have not been reported for Lake Michigan (Schelske 1975). On the other hand, some changes in the phytoplankton flora were apparent from collections made more than 40 years ago (Stoermer and Yang 1969).

Many of the environmental changes associated with nutrient enrichment probably occurred in the last 30 years, particularly in the phytoplankton (Schelske 1975). Nuisance blooms of Stephanodiscus hantzschii and S. binderanus first became evident in the Chicago water intakes in 1956. Possibly, the most obvious and pronounced change in phytoplankton species composition occurred within the last 15 years, i.e., the shift in the summer phytoplankton communities dominated by diatoms to those dominated by blue-green and green algae. Such a shift in species composition was predicted by Schelske and Stoermer (1971) as the result of silica depletion in surface waters that was caused by phosphorus enrichment and increased growth of diatoms. The associated changes in the standing crop and species composition at the primary producer level probably affect higher trophic levels, particularly the zooplankton; but some of these effects have been attributed to fish predation (Gannon 1972).

The shift in phytoplankton species composition, which occurs in late summer and early fall, has been verified several times in published studies (Stoermer 1972, Schelske et al. 1976, Conway et al. 1977), and is also verified in Part 2 of this report. Recent analyses of historical data on silica concentrations in Lake Michigan indicate that environmental conditions in the open waters changed rapidly after the mid 1950s. The historical data indicate that summer silica concentrations decreased rapidly from 1954-55 to 1969, changing summer epilimnetic waters in 15 years or less from those that were rich in silica to those in which silica concentrations limited diatom growth (Schelske et al. 1980). This relatively recent change at first appears to be inconsistent with some preconceived notions about the lake; however, it is consistent with the phytoplankton data from Chicago and with historical phosphorus loadings that have been simulated by Chapra (1977). The rapid decline in silica concentration appears to be correlated with increased phosphorus loadings from domestic wastes and the introduction of phosphate detergents, and therefore to have been the result of increased phosphorus loadings in the last 25 or 30 years.

Although it is generally accepted that the southern part of Lake Michigan has been affected more by the combined impact of anthropogenic materials than the northern part, there are relatively few studies that have addressed this problem. From the standpoint of nutrients and phytoplankton species composition, it was shown in 1969 that silica was depleted in the southern and northern epilimnetic waters (Schelske and Callender 1970) and that blue-green algae were a major component of the phytoplankton in northern Lake Michigan in September 1973 (Schelske et al. 1976). This shift in species composition of phytoplankton was reported in southern Lake Michigan during 1970 (Stoermer

1972). Stoermer and Yang (1969) found that phytoplankton composition in the southern part of the lake had been modified more than in the northern, but that the greatest effects were found in harbors and nearshore areas, particularly those in the southern part.

The purpose of our study was mainly to characterize northern Lake Michigan with respect to selected physical-chemical conditions and the standing crop and species composition of the phytoplankton. The data, along with those collected by Rockwell et al. (1980), will be important for their usefulness as reference points for comparison of past and future studies of Lake Michigan. In addition, data in this report are used to describe seasonal and spatial relationships of nutrients and phytoplankton in the lake. Such information is essential as a basis for the evaluation of trophic state and water quality (Bartone and Schelske 1982).

STATION SELECTION

Stations for study in northern Lake Michigan were selected to address several questions related to physical, chemical, and biological conditions in the open-lake, inshore-offshore differences, and influences of hydrologic exchange with Lake Huron through the Straits of Mackinac. Open-lake data are needed to determine whether there have been changes in different characteristics of the lake with time (Schelske et al. 1980), and to answer questions on the state of the lake. Nearshore stations were selected to determine the extent of inshore-offshore differences in chemical and biological constituents. These data are needed to determine the importance of nearshore loading on nearshore processes and the standing crop of phytoplankton.

Four transects of east-west stations were selected to study the distribution of open-lake variables in space and time. These transects were approximately equidistant, and ran between natural physiographic features, either points on the shoreline or islands in the lake (Fig. 1). Some transects ended at islands because we wanted to determine whether inshore-offshore differences were present when shoreline sources of nutrient loading were reduced.

A north-south transect running south from Beaver Island was included so we could determine if the chemical and biological properties of water on this transect were different from those in other parts of the lake. The pattern of water movement near this transect is generally directed northward, whereas flow of water is generally to the south at the west end of the east-west Beaver Island transect.

In total, 65 stations were selected for study. Forty-five of these stations were in the main part of the lake and 25 were in the area west of the Straits of Mackinac (Fig. 1). Sampling depths and number of depths for each station are listed in Table 1.

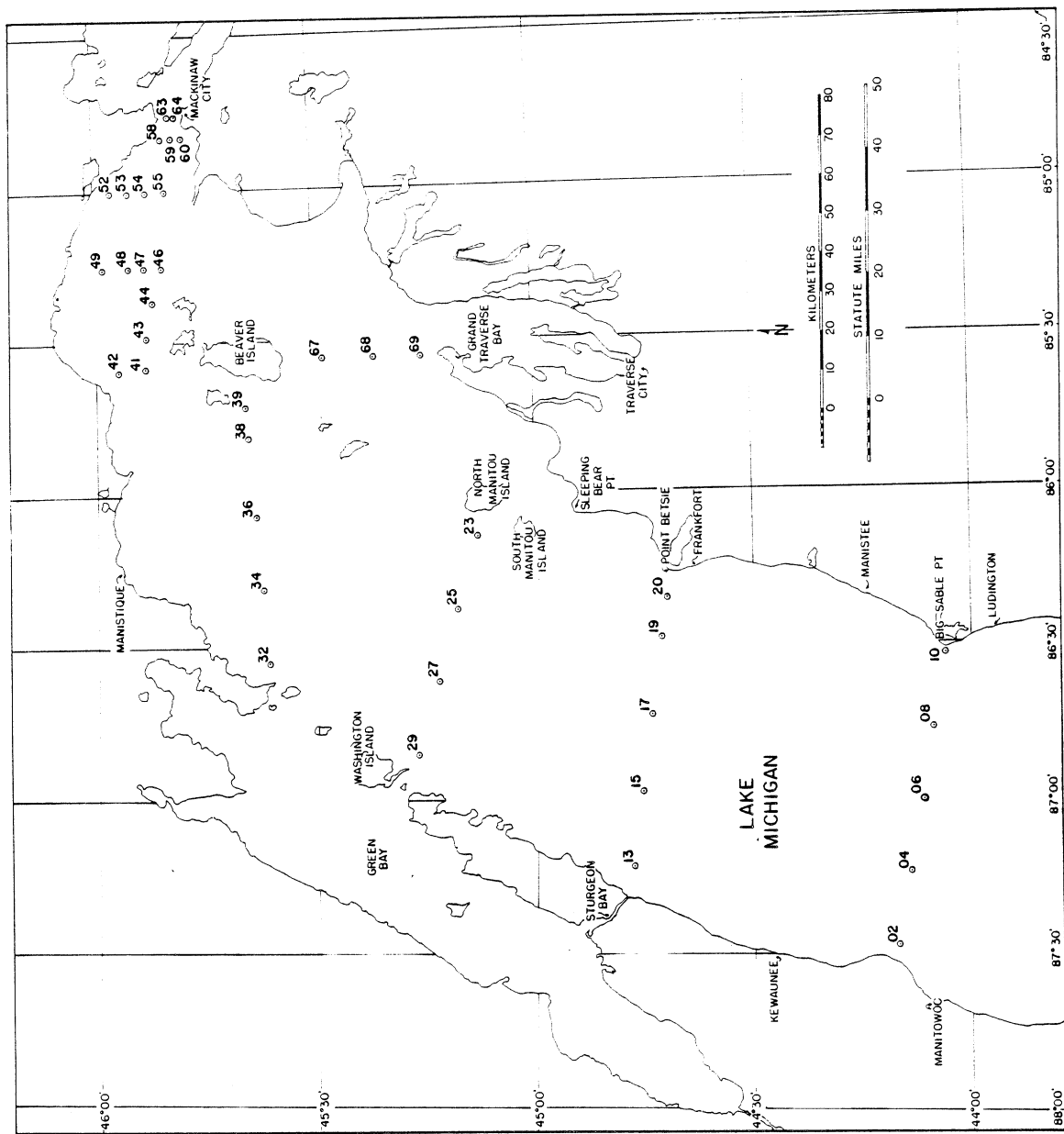


FIG. 1. Map of stations in northern Lake Michigan sampled in 1976 by the Great Lakes Research Division, University of Michigan, as part of a study sponsored by the Environmental Protection Agency. Stations located at 7.3-m depth at the ends of transects are not shown.

Nearshore stations were placed at the end of each transect, including those transects west of the Straits of Mackinac. These nearshore stations are not shown on Figure 1 and, with the exception of Station 30 located near Washington Island, were located at a depth of 7.3 m.

One master station was selected on each of the four east-west transects. Master stations were included to investigate the vertical structure in greater detail than could be accommodated within the time available for sampling at all stations. As many as 17 depths were sampled at one master station (Table 1) and it would not have been possible to sample with this intensity at every station. Master stations were Stations 6, 17, 25, and 36 (Fig. 1).

DISCUSSION

The intent of this report and the accompanying report by Stoermer (Part 2) is to characterize northern Lake Michigan with respect to selected physical-chemical conditions and the standing crop and species composition of phytoplankton. These studies provide a reference point for future and past studies of Lake Michigan, and characterize seasonal and spatial relationships of environmental conditions in Lake Michigan. To be consistent with these purposes, it was deemed essential that all of the data be presented in some form in this report.

Presentation of the extensive physical and chemical data collected to meet the purposes of the study is a fairly large task. Approximately 1,500 data points were obtained for 10 different variables, meaning that in total 15,000 data points were available for analysis. These data are presented under three headings on SPATIAL DISTRIBUTION, SEASONAL CHANGES, and STRAITS OF

TABLE 1. Locations and depths of stations sampled in northern Lake Michigan during 1976.

| Station | Latitude | Longitude | Depth (m) |
|---------|-----------|-----------|-----------|
| 01 | 44° 10.5' | 87° 30.4' | 7.3 |
| 02* | 44° 10.3' | 87° 28.4' | 29 |
| 03 | 44° 09.3' | 87° 21.2' | 100 |
| 04* | 44° 08.4' | 87° 14.0' | 166 |
| 05 | 44° 07.5' | 87° 06.7' | 179 |
| 06* | 44° 06.9' | 86° 59.9' | 182 |
| 07 | 44° 06.3' | 86° 53.0' | 150 |
| 08* | 44° 05.4' | 86° 46.0' | 161 |
| 09 | 44° 04.5' | 86° 39.0' | 134 |
| 10* | 44° 03.6' | 86° 32.0' | 48 |
| 11 | 44° 03.6' | 86° 31.3' | 7.3 |
| 12 | 44° 47.5' | 87° 17.8' | 7.3 |
| 13* | 44° 47.0' | 87° 12.7' | 42 |
| 14 | 44° 46.3' | 87° 05.4' | 109 |
| 15* | 44° 45.6' | 86° 58.0' | 170 |
| 16 | 44° 44.9' | 86° 50.7' | 259 |
| 17* | 44° 44.2' | 86° 43.3' | 274 |
| 18 | 44° 43.5' | 86° 35.9' | 254 |
| 19* | 44° 42.8' | 86° 28.5' | 101 |
| 20* | 44° 42.0' | 86° 21.1' | 168 |
| 21 | 44° 41.5' | 86° 15.8' | 7.3 |
| 22 | 45° 07.2' | 86° 04.4' | 7.3 |
| 23* | 45° 07.7' | 86° 08.0' | 12 |
| 24 | 45° 09.3' | 86° 15.5' | 73 |
| 25* | 45° 10.7' | 86° 22.5' | 198 |
| 26 | 45° 12.2' | 86° 30.0' | 177 |
| 27* | 45° 13.4' | 86° 36.8' | 120 |
| 28 | 45° 14.8' | 86° 44.0' | 53 |
| 29* | 45° 16.2' | 86° 51.4' | 30 |
| 30* | 45° 17.6' | 86° 57.7' | 32 |
| 31 | 45° 36.4' | 86° 35.8' | 7.3 |
| 32* | 45° 36.7' | 86° 32.7' | 33 |
| 33 | 45° 37.1' | 86° 25.5' | 67 |
| 34* | 45° 37.5' | 86° 18.0' | 83 |
| 35 | 45° 37.9' | 86° 10.7' | 122 |
| 36* | 45° 38.2' | 86° 03.5' | 105 |
| 37 | 45° 38.7' | 85° 54.0' | 96 |
| 38* | 45° 39.0' | 85° 48.3' | 13 |
| 39* | 45° 39.4' | 85° 42.6' | 47 |
| 40 | 45° 39.8' | 85° 37.1' | 7.3 |
| 41* | 45° 53.3' | 85° 35.2' | 35 |
| 42* | 45° 57.0' | 85° 35.2' | 26 |
| 43* | 45° 52.7' | 85° 28.5' | 30 |

TABLE 1. (continued).

| Station | Latitude | Longitude | Depth (m) |
|---------|-----------|-----------|-----------|
| 44* | 45° 51.4' | 85° 22.0' | 28 |
| 45 | 45° 48.6' | 86° 15.0' | 7.3 |
| 46* | 45° 51.2' | 86° 15.0' | 24 |
| 47* | 45° 53.7' | 86° 15.0' | 37 |
| 48* | 45° 56.0' | 86° 15.0' | 29 |
| 49* | 45° 58.9' | 86° 15.0' | 24 |
| 50 | 46° 01.4' | 86° 15.0' | 14 |
| 51 | 45° 59.4' | 85° 00.0' | 7.3 |
| 52* | 45° 57.5' | 85° 00.0' | 19 |
| 53* | 45° 55.0' | 85° 00.0' | 13 |
| 54* | 45° 52.5' | 85° 00.0' | 24 |
| 55* | 45° 50.0' | 85° 00.0' | 62 |
| 56 | 45° 47.1' | 85° 00.0' | 7.3 |
| 57 | 45° 51.4' | 84° 49.4' | 13 |
| 58* | 45° 50.1' | 84° 49.4' | 25 |
| 59* | 45° 48.8' | 84° 49.4' | 43 |
| 60* | 45° 47.4' | 84° 49.4' | 19 |
| 61 | 45° 46.2' | 84° 49.4' | 9.0 |
| 62 | 45° 49.8' | 84° 45.0' | 9.0 |
| 63* | 45° 49.1' | 84° 45.0' | 66 |
| 64* | 45° 48.5' | 84° 45.0' | 26 |
| 65 | 45° 47.7' | 84° 45.0' | 7.3 |
| 66* | 45° 34.8' | 85° 33.5' | 7.3 |
| 67* | 45° 29.0' | 85° 33.4' | 124 |
| 68* | 45° 21.8' | 85° 33.2' | 79 |
| 69* | 45° 15.0' | 85° 33.1' | 38 |
| 70* | 45° 13.0' | 85° 33.0' | 7.3 |

*Biological and chemical stations, at remaining stations only BT casts were made routinely. Depths sampled are indicated on figures in report.

MACKINAC. Data on the 25 stations in the Straits of Mackinac section are presented separately because some conditions at these stations differed from those in the main lake as the result of inflow and mixing of water from Lake Huron. All data from the main lake stations (Stations 1 to 40 and 66 to 70) are utilized under headings on SPATIAL DISTRIBUTION and SEASONAL CHANGES.

In the section on SPATIAL DISTRIBUTION, data are presented as isopleths for different variables on depth-distance plots for each of the five transects

that were sampled in the main lake. Only data for temperature, pH, nitrate nitrogen, soluble reactive silica, particulate silica, and chlorophyll a are presented in the depth-transect plots. Data on total phosphorus, total soluble phosphorus, ammonia nitrogen, and chloride were omitted either because variance was so large that attempting to plot isopleths appeared not to be warranted or because there was little variation (the case for chloride). However, cruise averages for all variables for nearshore as well as offshore stations are presented in Tables 2 to 11.

The discussion on SEASONAL CHANGES is based on comparison of seasonal changes at each of the four master stations in the main part of the lake (Stations 6, 17, 25, and 36) and on means and standard deviations for each cruise that were obtained from data that had been stratified according to thermal conditions into epilimnetic, metalimnetic, and hypolimnetic components. These means and standard deviations, presented in Tables 2 to 11, provide data for comparison with other studies on the open waters of Lake Michigan.

METHODS

Water samples were taken with 5-liter Niskin bottles at predetermined depths starting at 5 m and at 5-, 10-, 20-, or 50-m intervals to the bottom except at nearshore stations where samples were obtained at 2 and 5 m. Sampling depths were spaced at 10- or 20-m intervals at the master stations and depths were adjusted so that 17 was the maximum number of Niskin bottles used per station. Specific depths are listed in Table 1. Water transparency was measured with a 30-cm white Secchi disc. Temperature was measured with a bathythermograph (BT), and in addition, temperature was measured with a

mercury thermometer in a bucket of surface water so the bathythermograph trace could be calibrated.

All methods used on the northern Lake Michigan cruises are described in a manual of field and laboratory procedures (Davis and Simmons 1979). Water samples were processed as illustrated in the flow chart (Fig. 2). Samples for soluble chemical analyses were filtered through 47-mm HA Millipore filters that were previously soaked and rinsed at least twice with distilled-deionized water. Filtered samples were stored at 4°C in Nalge conventional polyethylene bottles that were rinsed at least once with excess sample before filling.

A Corning Model 110 pH meter, equipped with a digital expanded scale and an automatic temperature compensator, was used on shipboard to measure pH immediately after raw water samples were taken (Fig. 2). Specific conductance, corrected to 25°C, was measured on shipboard with a Leeds and Northrup Model 4866-60 conductivity bridge. Subsurface light penetration was measured using a Licor model LI-192S underwater quantum sensor coupled with a Licor model LI-185 quantum meter. These measurements were not conducted at every station because of the time involved and the presumed predictability and constancy of the attenuation characteristics of Lake Michigan water. Measurements were not attempted in rough seas nor when it was impossible to obtain satisfactory time-averaged responses under changing cloud patterns.

Nutrient analyses were made on filtered samples with a Technicon AutoAnalyzer II equipped to measure five nutrients simultaneously -- nitrate plus nitrite nitrogen, ammonia nitrogen, soluble reactive silica, chloride, and soluble reactive phosphorus. Samples were stored in a refrigerator until analyses were run, usually within several hours after collection and always on the day of collection. Samples for total phosphorus were frozen and returned

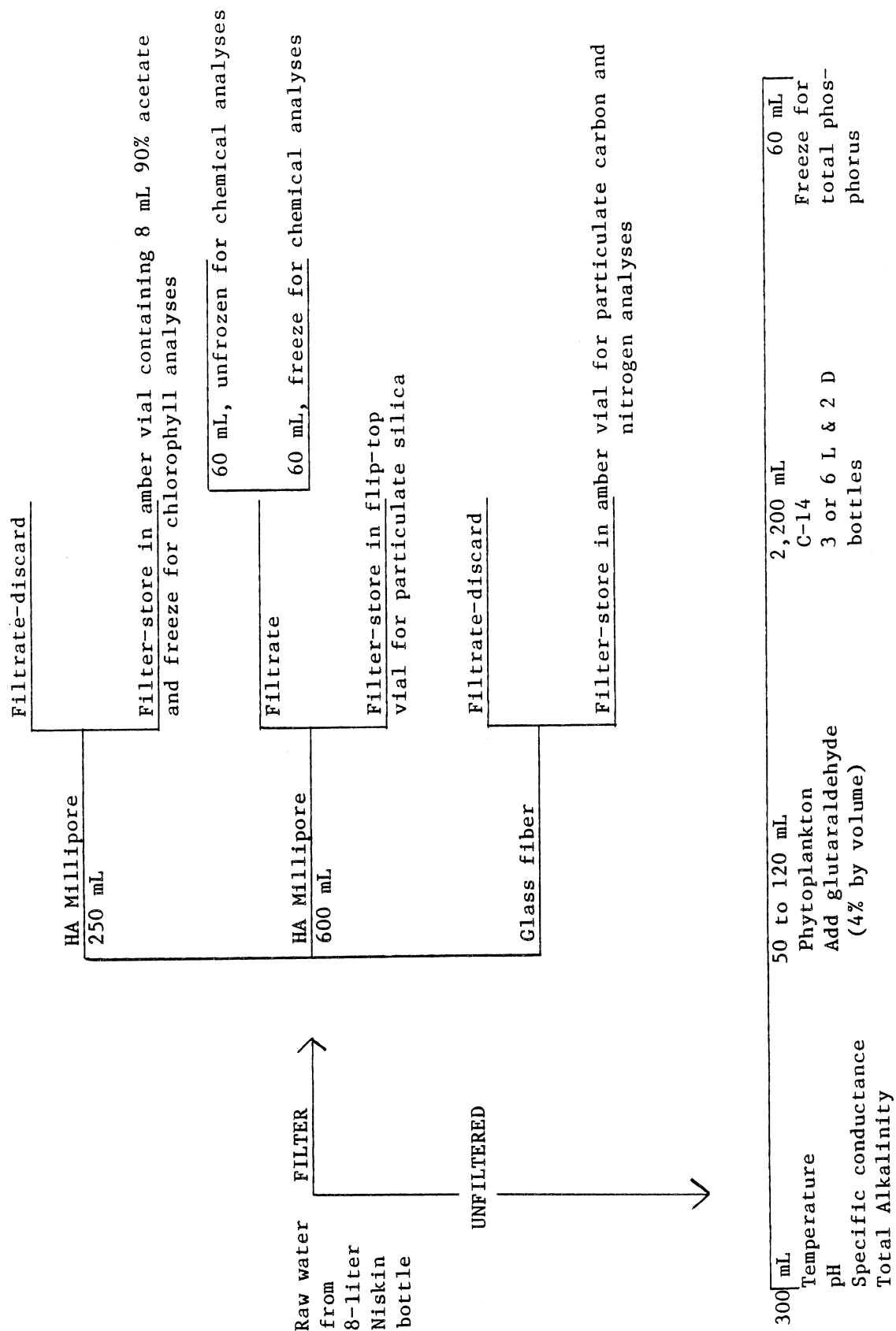


FIG. 2. Flow chart illustrating sample processing for study of water samples from northern Lake Michigan.

to Ann Arbor for analyses. Methods used for these chemical analyses are described by Davis and Simmons (1979), and specific information is presented in the following paragraphs.

Nitrate was measured by reducing it to nitrite with a copper-cadmium reduction column. The nitrite produced and the nitrite initially present in the sample were then determined by a diazotization-coupling reaction using sulfanilamide and N-1-naphthyl-ethylene diamine. The resulting colored complex was measured at 550 nm. Nitrite was not analyzed separately, as quantitatively insignificant values would be expected in non-polluted oxygenated waters (see Mortonson and Brooks 1980).

Ammonia and ammonium ions were measured by conversion of ammonium ions to ammonia in a basic medium. Ammonia reacts with hypochlorite and phenol to produce an indolphenol blue color which was measured at 630 nm. The reaction was catalyzed by nitro-prusside, and EDTA was added to prevent precipitation of alkali earth metals.

Silica was determined by reacting it with acidified molybdate to form a silicomolybdate complex that is reduced by ascorbic acid to an intense heteropoly blue and measured at 660 nm. Oxalic acid was added to destroy any phosphomolybdate.

Soluble reactive phosphorus was measured by formation of antimony-phosphomolybdate complex in acid medium which was reduced by ascorbic acid and measured at 880 nm.

Chloride was determined from its reaction with mercuric thiocyanate that forms ionized but soluble mercuric chloride. The released thiocyanate in the

presence of a ferric ion reacts to form a red complex, $\text{Fe}(\text{SCN})_3$. The resulting color was measured at 480 nm.

Chemical analyses for total phosphorus and total soluble phosphorus were performed in the laboratory on frozen samples. Samples were thawed, concentrated by evaporation, and then digested with potassium persulfate for one and a half hours in an oven at 110°C , as modified from Menzel and Corwin (1965). The samples were then analyzed for soluble reactive phosphorus on an AutoAnalyzer I. The blue color produced was measured at 630 nm.

Samples for total particulate silica were collected on 47-mm HA Millipore filters and placed in plastic flip-top vials. In the laboratory, particulate silica was decomposed with HNO_3HF reagent. The excess hydrofluoric acid was complexed with boric acid. Silica concentrations in the decomposed samples were determined by atomic absorption spectrometry using a nitrous oxide-acetylene flame (Simmons 1980).

Samples for chlorophyll a (250 mL) were filtered onto 47-mm HA Millipore filters that were then extracted in 90 percent acetone buffered with magnesium carbonate. Samples were stored in amber vials in the dark at -20°C for a minimum of 12 hours. On the first cruise, some chlorophyll determinations were made on ship; later all were done in our laboratory in Ann Arbor. Analyses were switched to the laboratory because all the work could not be completed on board ship and, in addition, it was presumed that better precision would be obtained under laboratory conditions. Prior to analysis, chlorophyll samples were centrifuged, and then 5 mL were transferred to sample cuvettes and read in a modified Turner Model 111 fluorometer. Samples were subsequently acidified with one or two drops of 50 percent V/V HCl and read in the fluorometer for phaeopigment determination (Strickland and Parsons 1968).

All results were corrected for phaeophytin. The phaeophytin fraction generally represented a small proportion of the chlorophyll a, so possible errors resulting from the addition of excess amounts of hydrochloric acid (Riemann 1978) would probably be small.

SPATIAL DISTRIBUTION

CRUISE 1, 22-28 APRIL

Water Temperature

On the first cruise, water temperatures were characterized by a monotonous homogeneity. No vertical structure was evident and open-lake temperatures over the four main lake transects ranged from 2.2 to 3.8°C. Coldest temperatures ($<3^{\circ}\text{C}$) were found on the two northernmost transects at the mid-lake stations and on the Point Betsie transect at Stations 13 and 14. Water temperatures exceeded 4°C only at nearshore locations, with the maximum occurring at the southernmost transect (Fig. 3). An exception to the pattern of warmer nearshore waters was found at the North Manitou Island transect, which is atypical in that it ends at a deep water passage to Green Bay and at an island surrounded by deep water.

Without the atypical North Manitou Island transect, temperatures at nearshore stations decreased with increase in latitude which would be expected as the result of differential warming in the lake. Nearshore temperatures exceeded 7 or 8°C on the southernmost transect from Big Sable Point (Fig. 3), 6°C on the next transect northward, and 5°C at the nearshore station off Beaver Island.

The thermal bar, a characteristic feature of the spring warming cycle in the Great Lakes, was not well developed during this cruise because temperatures $>4^{\circ}\text{C}$ were present only at some of the nearshore stations that were 7.3 m deep.

Hydrogen Ion Concentration

On the first cruise, the pH meter malfunctioned so data are available only for the Big Sable Point transect. At the three deepest stations on this transect, there was some indication that values for pH were larger for samples collected above 100 m than for those collected below 100 m. Differences, if present, were small and amounted to 0.05 pH units at most (Fig. 4). Over the transect, the absolute range in measured pH values for the offshore stations was 8.22 to 8.32. At the two nearshore stations pH was >8.55 , larger than at the offshore stations. These high pH values were only found at nearshore locations where water temperatures were $>4^{\circ}\text{C}$.

Nitrate Nitrogen

Although water temperatures on the first cruise were nearly homothermal at the offshore stations, this pattern of homogeneity was not characteristic for the spatial distribution of nitrate. Vertical distributions of nitrate were uniform, which was also true for water temperature; however, spatial distributions of nitrate differed from temperature in that there was an east-west gradient of nitrate concentration. Concentrations of nitrate were larger on the eastern side of the three transects located south of Green Bay than on the western side. The largest values were present on the eastern side of the southernmost transect and ranged from 0.27 to 0.33 mg/liter at Stations 08 and 10 (Fig. 5). Values as large as 0.25 mg/liter were found on the eastern portions of the Point Betsie and N. Manitou Island transects. On the western side of the lake concentrations were 0.20 mg/liter or less. This pattern of nitrate distribution clearly identifies a water mass with relatively high nitrate on the east side of the lake.

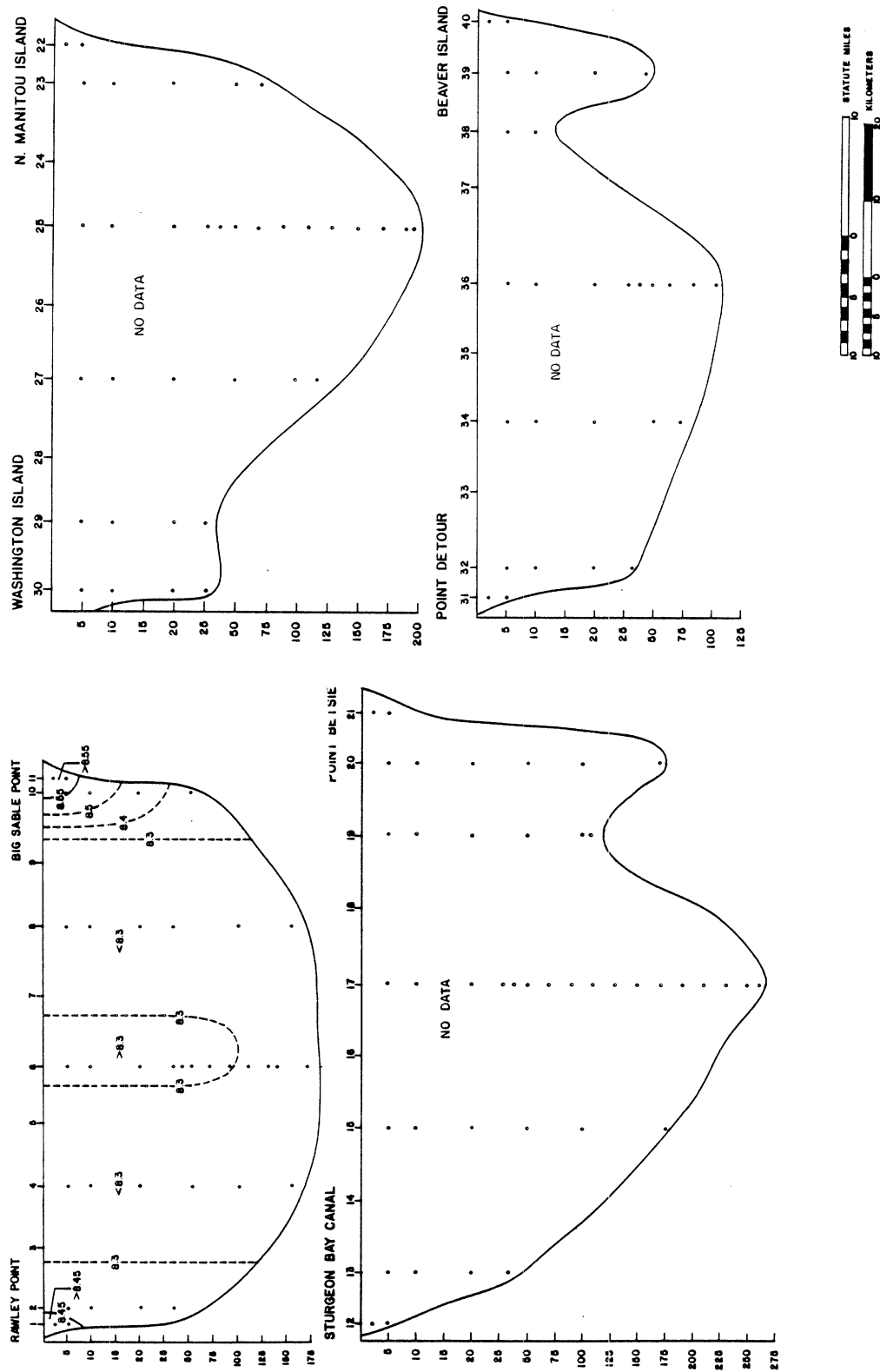


FIG. 4. Hydrogen ion concentration (pH) on Cruise 1, 22-28 April 1976.

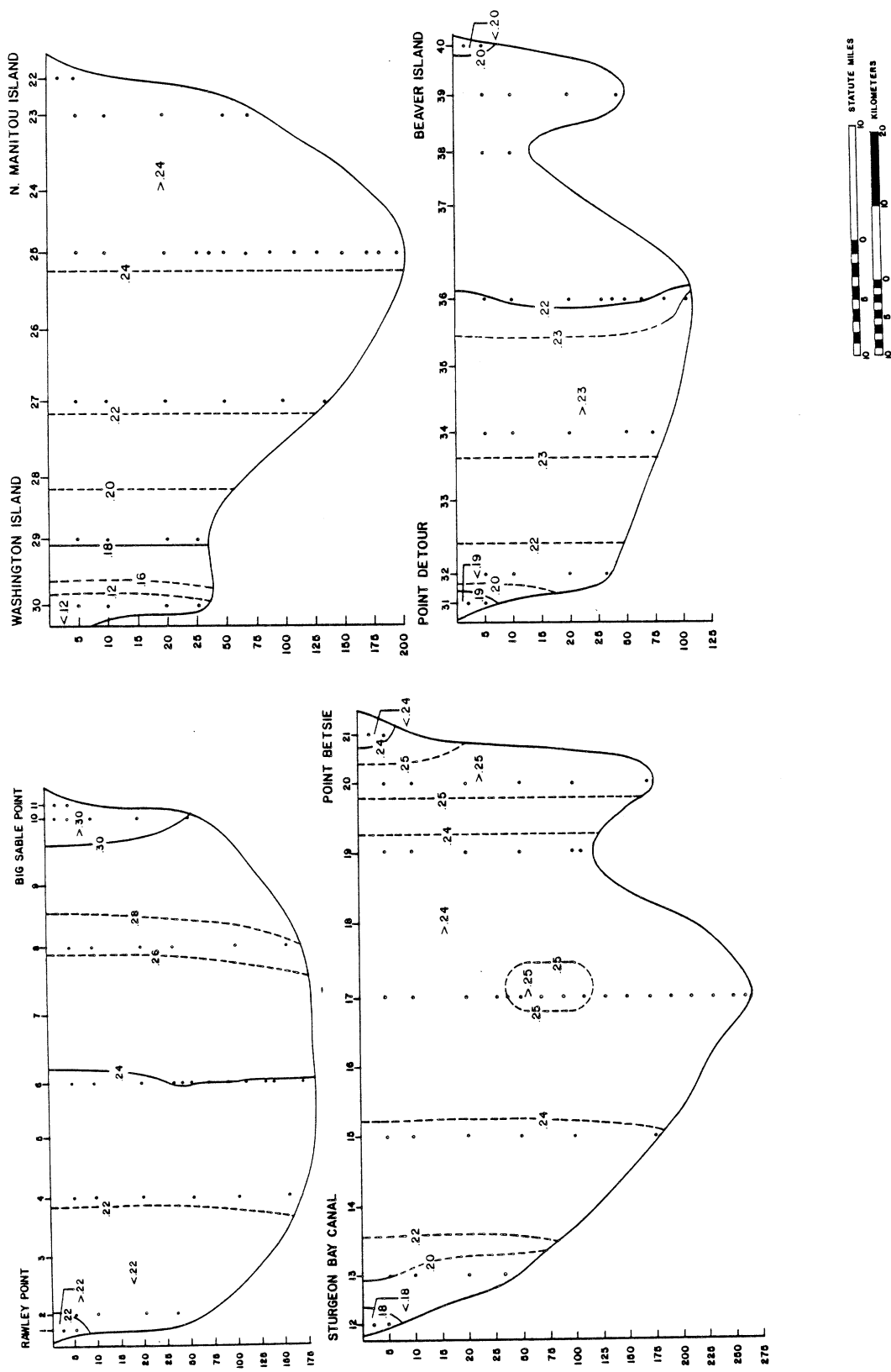


FIG. 5. Nitrate nitrogen (mg NO₃-N/liter) on Cruise 1, 22-28 April 1976.

The origin of the low nitrate water is open to speculation. It could be water derived from Green Bay or from shallow waters in the northern part of the lake where phytoplankton utilization of nutrients was accelerated by earlier warming of waters than that which occurred in the deeper parts of the lake. Nutrient depletion is more rapid in shallow water because the ratio of surface area to volume is greater in shallower water than deeper waters which produces a greater volumetric decrease in nutrients in shallow waters. The observed east-west gradient was more pronounced than the nearshore depletion of nitrate that was present on some transects.

Soluble Reactive Silica

The spatial variability of silica on transects and between transects was much greater than that found for either temperature or nitrate in April. Largest concentrations were found at the deepest station (Station 17) and at stations deeper than 70 m on the eastern side of the three transects located south of Green Bay (Fig. 6). This pattern of lowest concentrations at the stations on the western side of these transects was similar to that noted for nitrate; however, the relative differences among areas was much greater for silica than for nitrate. Silica concentrations at the western nearshore stations on these three transects were generally <0.4 mg/liter, much less than concentrations that exceeded 1.0 mg/liter at the remaining stations, with the exception of nearshore stations on the eastern side of the Point Sable transect. Smallest silica concentrations (<0.2 mg/liter) were found in the nearshore zone at Stations 12 and 30 at the western side of the lake. Because the chemistry at Station 30 probably reflects the chemical characteristics of adjacent Green Bay water, it can be concluded that the origin of low silica

water for the North Manitou Island transect is partly the result of outflow from Green Bay. Low concentrations at shallow nearshore stations can be attributed to local nearshore processes, but at Station 30, the depth affected is 30 m and therefore this mass of low silica water does not appear to have resulted from local processes.

Another unique feature of silica distribution in relation to that for nitrate and temperature was the relatively low values on the Beaver Island transect. This northernmost shallow transect had smaller silica concentrations than those found at the deeper transects to the south. Maximum concentrations were <0.9 mg/liter and smaller concentrations, generally <0.6 mg/liter, were found at the shallower stations (Fig. 6).

Particulate Silica

Like other variables measured on the cruise, the vertical distribution of particulate silica was generally uniform at individual stations. Concentrations at stations with depths >100 m generally ranged from <0.3 to 0.5 mg/liter (Fig. 7). Concentrations >0.5 mg/liter were found only at nearshore stations and in subsurface waters on the Beaver Island transect. The largest nearshore values were found on the Big Sable Point transect where concentration exceeded 2 mg/liter at the nearshore stations at each end of the transect. The large nearshore values resulted either from large diatom standing crops or to large contributions from nearshore sources of minerals. It is likely that the large values can be attributed to diatoms because standing crops of chlorophyll a exceeded 12 and 20 $\mu\text{g/liter}$ at these stations (see Fig. 8).

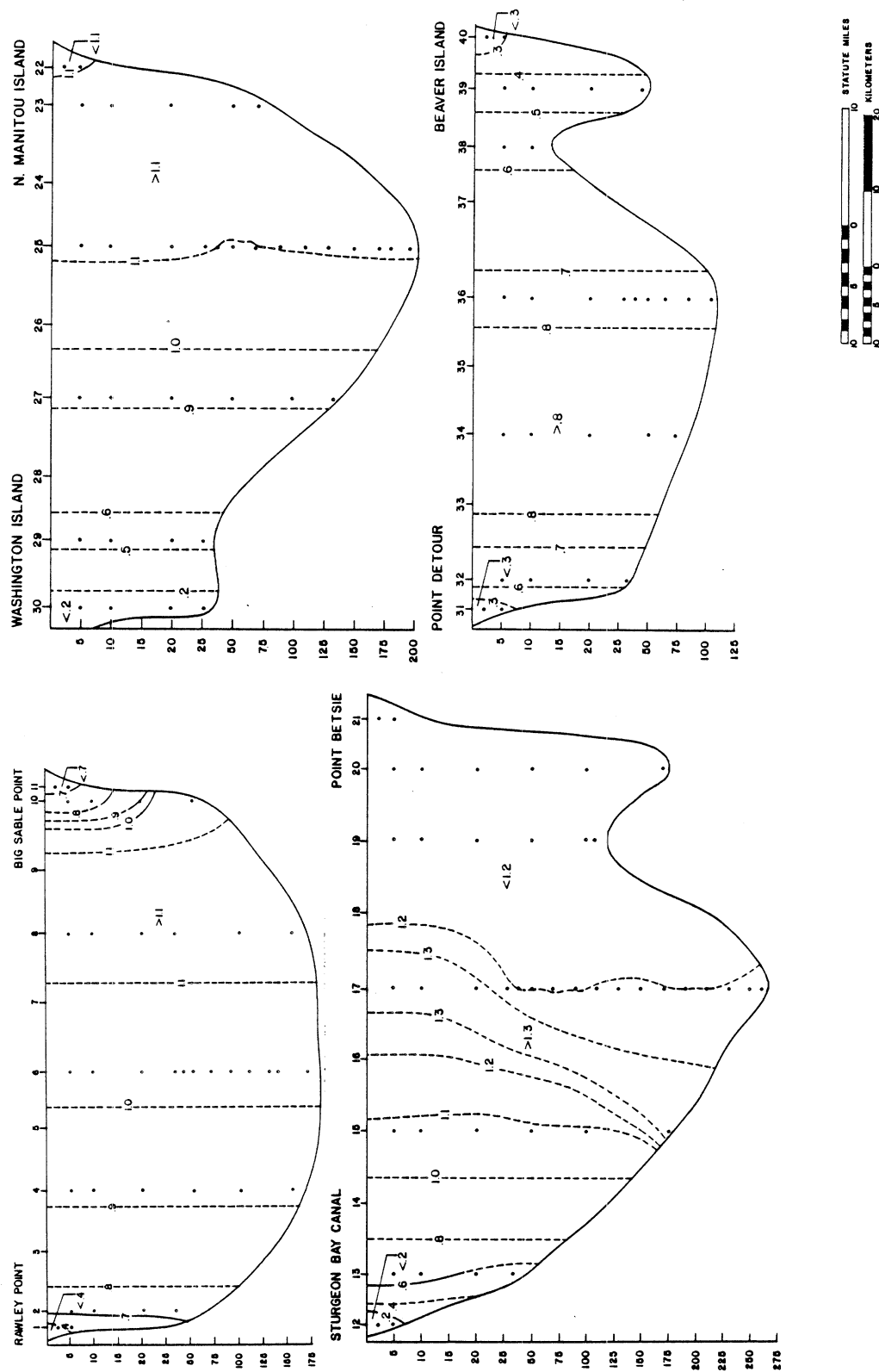


FIG. 6. Soluble reactive silica (mg SiO₂/liter) on Cruise 1, 22-28 April 1976.

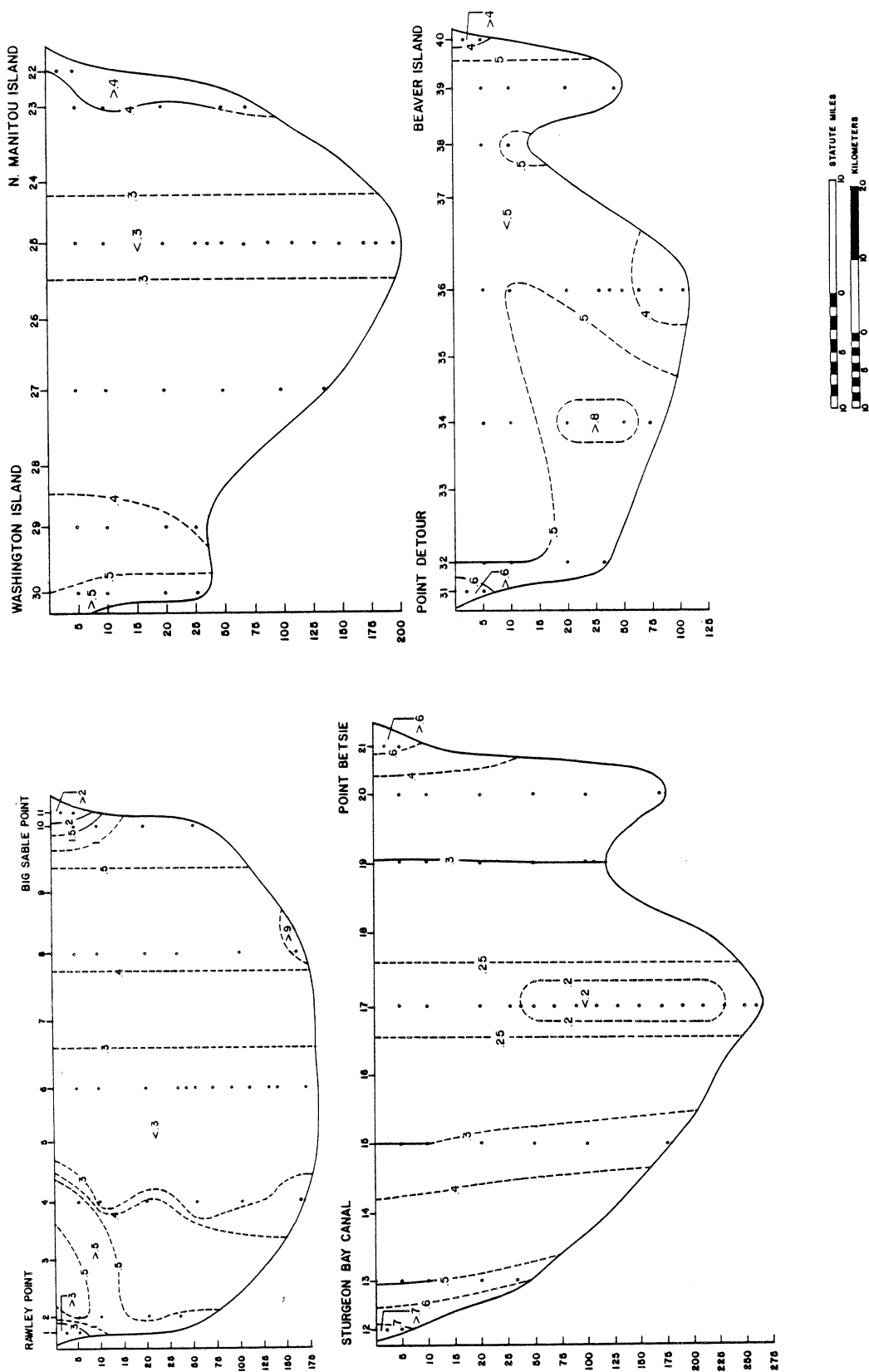


FIG. 7. Particulate silica (mg SiO₂/liter) on Cruise 1, 22-28 April 1976.

Chlorophyll a

Like the physical and chemical variables measured in April, the vertical distribution of chlorophyll a was not highly variable. Spatial variability among stations and transects, however, was much greater than that found for the other variables measured. Concentrations of chlorophyll a ranged from $<0.2 \mu\text{g/liter}$ at Station 8 on the eastern side of the Big Sable Point transect to 10 to 20 $\mu\text{g/liter}$ at the shallow nearshore stations on the Big Sable Point transect (Fig. 8). Concentrations $<1.0 \mu\text{g/liter}$ were restricted to the deepest midlake stations and were not present on the shallow northern transect off Beaver Island where concentrations ranged from 2 to 5 $\mu\text{g/liter}$.

On the western ends of the three deep transects south of Washington Island, chlorophyll a concentrations $>2 \mu\text{g/liter}$ were found at stations with depths shallower than 50 m (Fig. 8). At Stations 29 and 30 near Death's Door, concentrations were 4 $\mu\text{g/liter}$ or greater, indicating that water enriched with chlorophyll a was flowing out of Green Bay. On the eastern end of the three deep transects, chlorophyll a levels $>2 \mu\text{g/liter}$ were generally restricted to the shallow nearshore stations, with greater concentrations being found only at Station 10 off Big Sable Point.

Summary

Conditions during the first cruise were characterized by cold, isothermal waters with open-lake temperatures ranging from 2.2 to 3.8°C (Fig. 3). Temperatures exceeded 4°C only at the nearshore stations on the two southernmost transects and at one station off Beaver Island. Data for pH were available only for the southernmost transect where open-lake values were <8.35 and nearshore values ranged from 8.4 to 8.6 (Fig. 4).

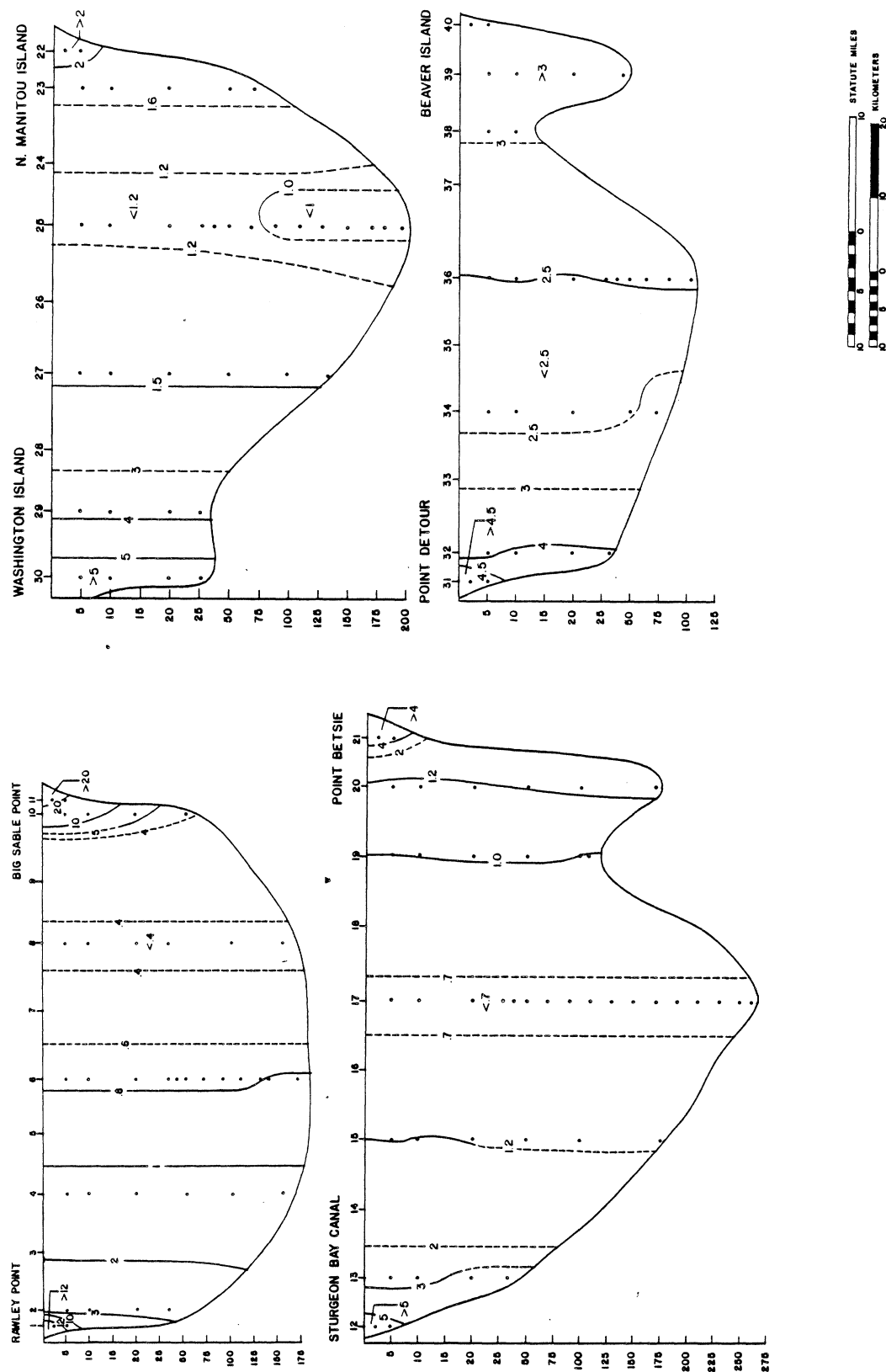


FIG. 8. Chlorophyll *a* (µg/liter) on Cruise 1, 22-28 April 1976.

Vertical distributions of nitrate and silica were uniform at individual stations as would have been expected in isothermal waters, but horizontally there was more variability for these nutrients than would be expected from the thermal patterns. On the three southernmost transects, the most pronounced feature in nitrate distribution was a decreasing gradient in concentrations from east to west (Fig. 5). Nitrate concentrations on the northernmost transect off Beaver Island were less than those on the transects to the south and were smaller for the nearshore stations than at the mid-transect stations. Spatial distributions of silica also showed a pattern of decreasing concentrations from east to west on the three southernmost transects, but depletion was also evident at nearshore stations on these transects as well as in the shallow waters over the entire northernmost transect off Beaver Island (Fig. 6). Concentrations of silica were lowest, <0.2 mg/liter, at the nearshore stations on the western ends of the two southernmost transects. Low concentrations at these and other stations corresponded with high levels of chlorophyll a (Fig. 8).

Chlorophyll a values were greatest at the nearshore stations with the largest concentrations, >12 and >20 $\mu\text{g/liter}$, being found off Rawley Point and Big Sable Point (Fig. 8). The smallest concentrations, <1.0 $\mu\text{g/liter}$, were found at the midlake stations on the two southern transects. Concentrations on the shallow Beaver Island transect were generally 2.5 $\mu\text{g/liter}$ or greater and, with the exception of the nearshore stations, were larger than those on the other three transects.

In the areas with high chlorophyll a concentrations silica levels were reduced compared to open-lake concentrations, as were nitrate levels. Largest concentrations of particulate silica (Fig. 7) were found on the Big Sable

Point transect at the two nearshore stations with the largest chlorophyll a concentrations (Fig. 8). On this transect, particulate silica concentrations were >2 and >3 mg SiO₂/liter where chlorophyll a concentrations were >12 and >20 μ g/liter. The large area with low soluble nutrients and high chlorophyll a off Death's Door was attributed to outflow of enriched water from Green Bay.

CRUISE 2, 2-7 JUNE

Water Temperature

On Cruise 2 in early June the thermal bar was well developed on all the east-west transects in the main lake (Fig. 9) with midlake temperatures on these transects being isothermal ($<5^{\circ}\text{C}$). Only on the Grand Traverse Bay transect was weak thermal stratification present at midtransect with surface water being $>7^{\circ}\text{C}$. Two instances of weak upwelling were observed: one at Station 10 near Big Sable Point, and the other at Station 70 near Lighthouse Point. Off Point Betsie and Lighthouse Point warmer waters were also found offshore than at the nearshore station. Surface nearshore waters, with the exceptions noted, generally ranged from 12 to 14°C with a mixed layer depth of 5 m or less.

Hydrogen Ion Concentration

The spatial distribution of pH closely paralleled that for water temperature in June. At the cold isothermal stations on the main lake transects and below the weakly stratified waters, values for pH were generally <8.4 (Fig. 10). In the deepest waters values were even lower, <8.3 . In nearshore waters and extending offshore where thermal stratification was weakly developed, values for pH were >8.4 . Largest values were found on the three southernmost transects where pH ranged from 8.5 to 8.6.

Nitrate Nitrogen

In early June the spatial distribution of nitrate was related to the thermal regime. Largest values for nitrate, 0.24 to 0.26 mg/liter, were found

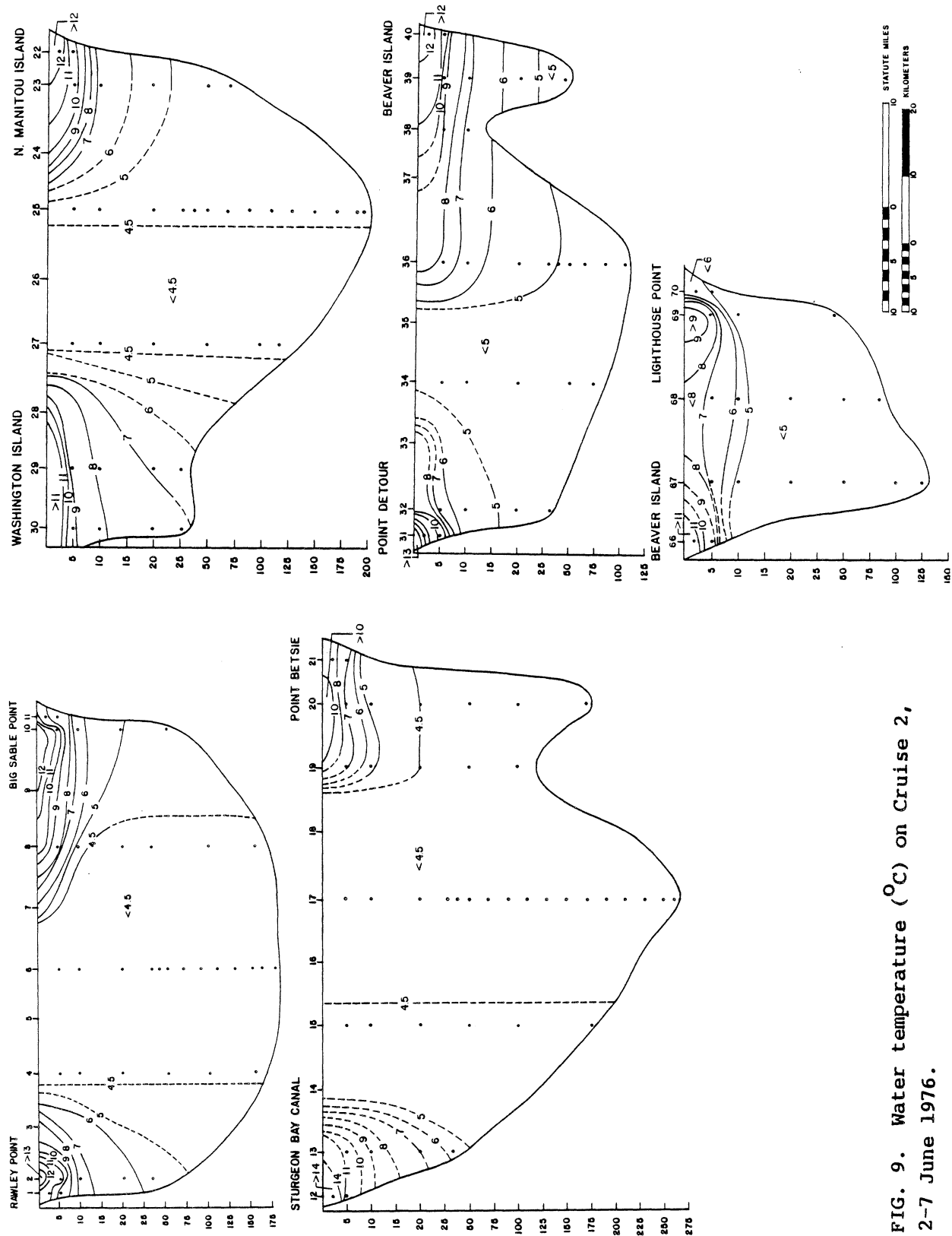


FIG. 9. Water temperature ($^{\circ}\text{C}$) on Cruise 2, 2-7 June 1976.

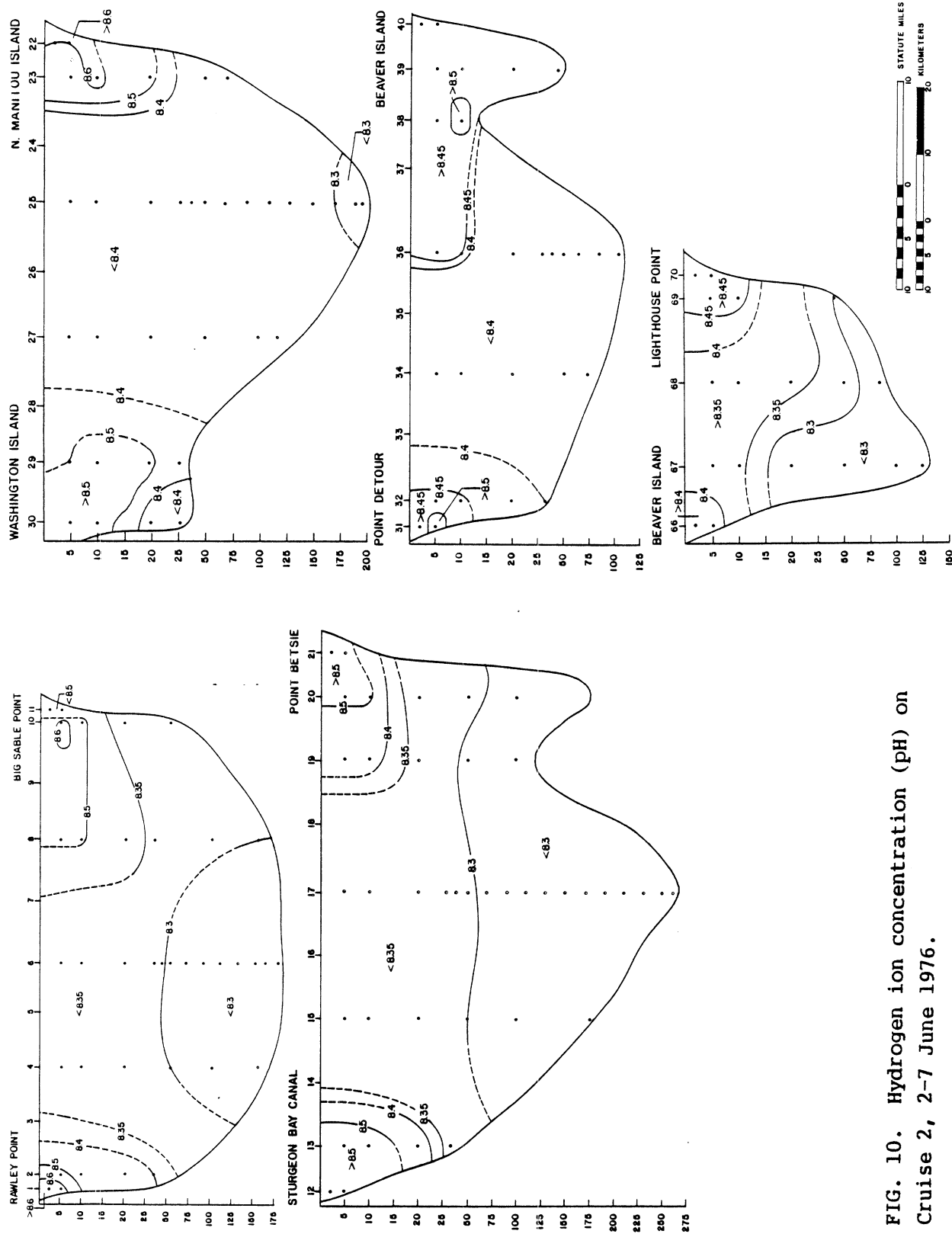


FIG. 10. Hydrogen ion concentration (pH) on Cruise 2, 2-7 June 1976.

at the isothermal stations on the three southernmost transects, whereas on the midlake portions of the shallower Beaver Island and Grand Traverse Bay transects concentrations were lower, ranging from 0.20 to 0.22 mg/liter (Fig. 11). The influence of thermal stratification was obvious in the distribution of nitrate on the Grand Traverse Bay transect; concentrations in the weakly stratified surface waters at mid transect were <0.21 mg/liter, slightly lower than the bottom waters.

Concentrations of nitrate in the nearshore waters varied greatly over the study area. Largest concentrations were found at the eastern end of the three southern transects similar to patterns observed in April and ranged from 0.18 to 0.22 mg/liter (Fig. 11). In contrast smallest concentrations, which ranged from 0.08 to 0.13 mg/liter, were found on the western ends of these transects. Concentrations <0.08 mg/liter at Station 12 and <0.10 mg/liter at Station 30 showed extreme nitrate depletion relative to open-lake values which ranged from 0.24 to 0.26 mg/liter. Smaller amounts of depletion were found at the nearshore stations on the Beaver Island transect and off Rawley Point on the southernmost transect.

Soluble Reactive Silica

Silica concentrations in early June ranged from a low of <0.1 mg/liter in nearshore waters to >1.1 mg/liter in offshore waters (Fig. 12). Largest concentrations were found at the deep isothermal stations on the three southern-most transects. In general, concentrations at these deep stations ranged from 0.9 to 1.1 mg/liter, but there was some suggestion of vertical stratification in near-bottom waters where concentrations as large as 1.8 mg/liter SiO_2 were found at Station 8 and 1.4 mg/liter were found at Station 25.

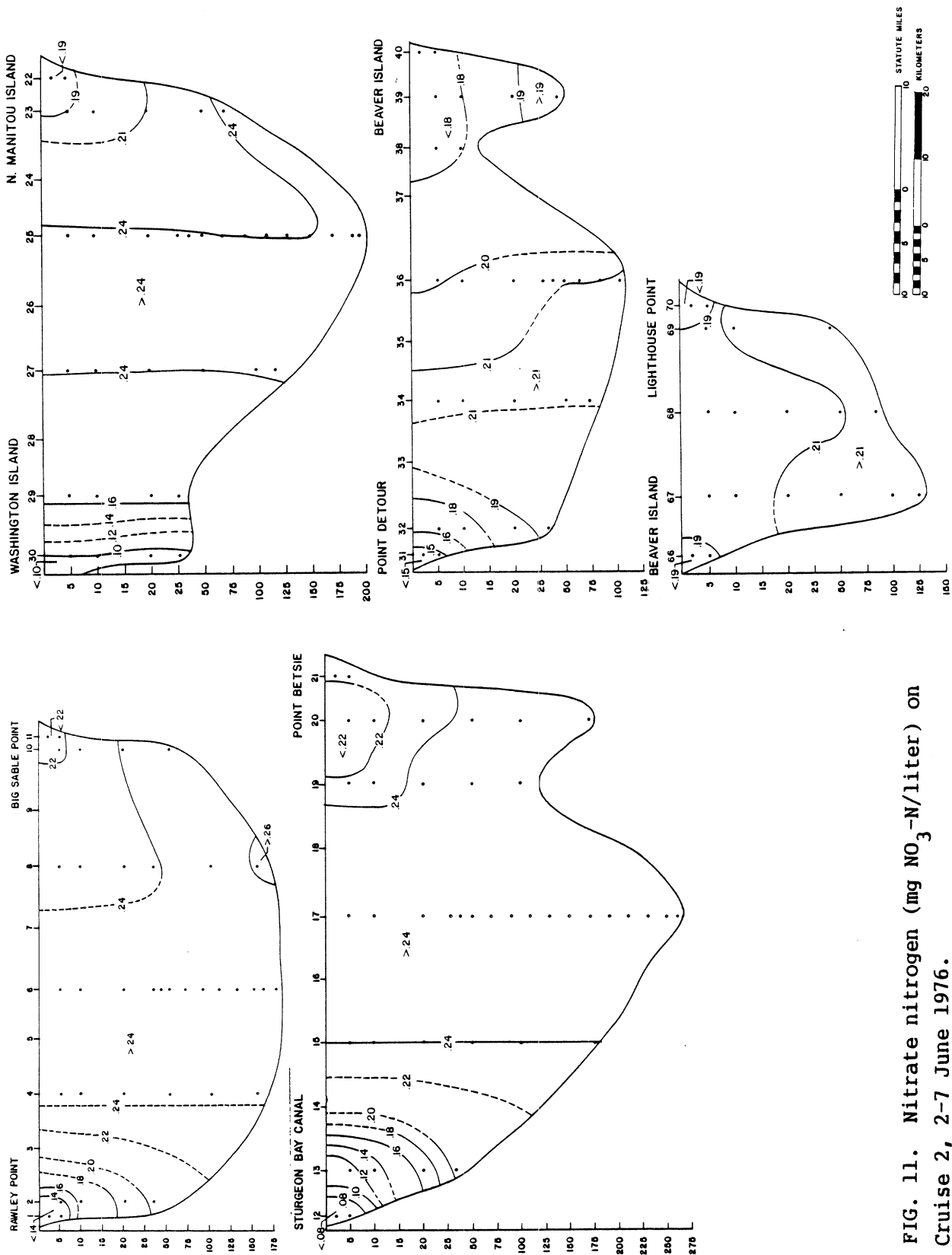


FIG. 11. Nitrate nitrogen (mg NO₃-N/liter) on Cruise 2, 2-7 June 1976.

On the three southernmost transects, concentrations of silica, like those for nitrate, were lower on the western than on the eastern sides of the transects. At the western station silica concentrations were <0.1 mg/liter or at levels that obviously would limit diatom growth (Fig. 12). On the eastern ends of these transects concentrations were larger; concentrations >1 mg/liter were found at Station 11, possibly the result of upwelled water (Fig. 9) and ranged from 0.5 to 0.8 mg/liter at the other nearshore locations.

In the shallow waters of the Beaver Island transect maximum concentrations were lower than those on the deeper transects to the south and ranged from 0.5 to 0.6 mg/liter; however, concentrations over most of the transect were <0.5 mg/liter (Fig. 12). Concentrations were also low on the Grand Traverse Bay transect, being <0.4 mg/liter in the surface waters, and increased generally from the surface to bottom, a distribution related to the existence of weak thermal stratification.

Particulate Silica

Compared to the spatial distributions for silica and nitrate (Figs. 11 and 12), the spatial distribution of particulate silica in June was very complex. Some form of vertical stratification in particulate silica was present at almost all stations and the absence of vertical structure was noted only at two or three isothermal stations (Stations 4, 15, and 17) on the two southernmost transects where depths were >150 m (Fig. 13). Vertical homogeneity at these deep stations was associated with the lowest values for particulate silica or with values that were generally <0.3 mg/liter.

Different spatial patterns were found for particulate silica on the east and west ends of the two southernmost transects. Concentrations on the west

side were somewhat higher than on the east, ranging from 0.6 to 0.8 mg/liter on the west to concentrations of 0.6 mg/liter or less on the east (Fig. 13). Isopleths on the west side of these two transects were vertical, with the highest concentrations nearshore. On the east side isopleths extending toward mid lake tended to be horizontal, with greatest concentrations occurring at depths of 10-20 m. On the three remaining transects concentrations generally tended to increase with depth. Largest concentrations, >0.8 mg/liter, were found at Station 30 off Death's Door. Lowest concentrations on these transects were in general found at the stations with the highest water temperatures, i.e., in the surface waters that were thermally stratified.

Chlorophyll a

Vertical distributions of chlorophyll a in June were relatively homogeneous at the isothermal midlake stations and exhibited a subsurface maximum at the thermally stratified stations. Concentrations at the isothermal midlake stations on the three southernmost transects varied at least fourfold, ranging from 0.6 mg/liter at Station 27 (Fig. 14) to 2.4 mg/liter at Station 17.

At the thermally stratified nearshore stations a subsurface chlorophyll maximum was found at depths ranging from 10 to 20 m. Concentrations of chlorophyll in this layer ranged from 4 to 6 mg/liter at Stations 2, 10, 13, 20, 23, and 69 (Fig. 14). Subsurface maxima were located at stations inside the thermal bar and at depths above the 5 to 7°C isopleths.

Like the distribution of particulate silica (Fig. 13) there was some suggestion of vertical isopleths for chlorophyll a at the stations on the western side of the two southernmost transects (Fig. 14). The vertical

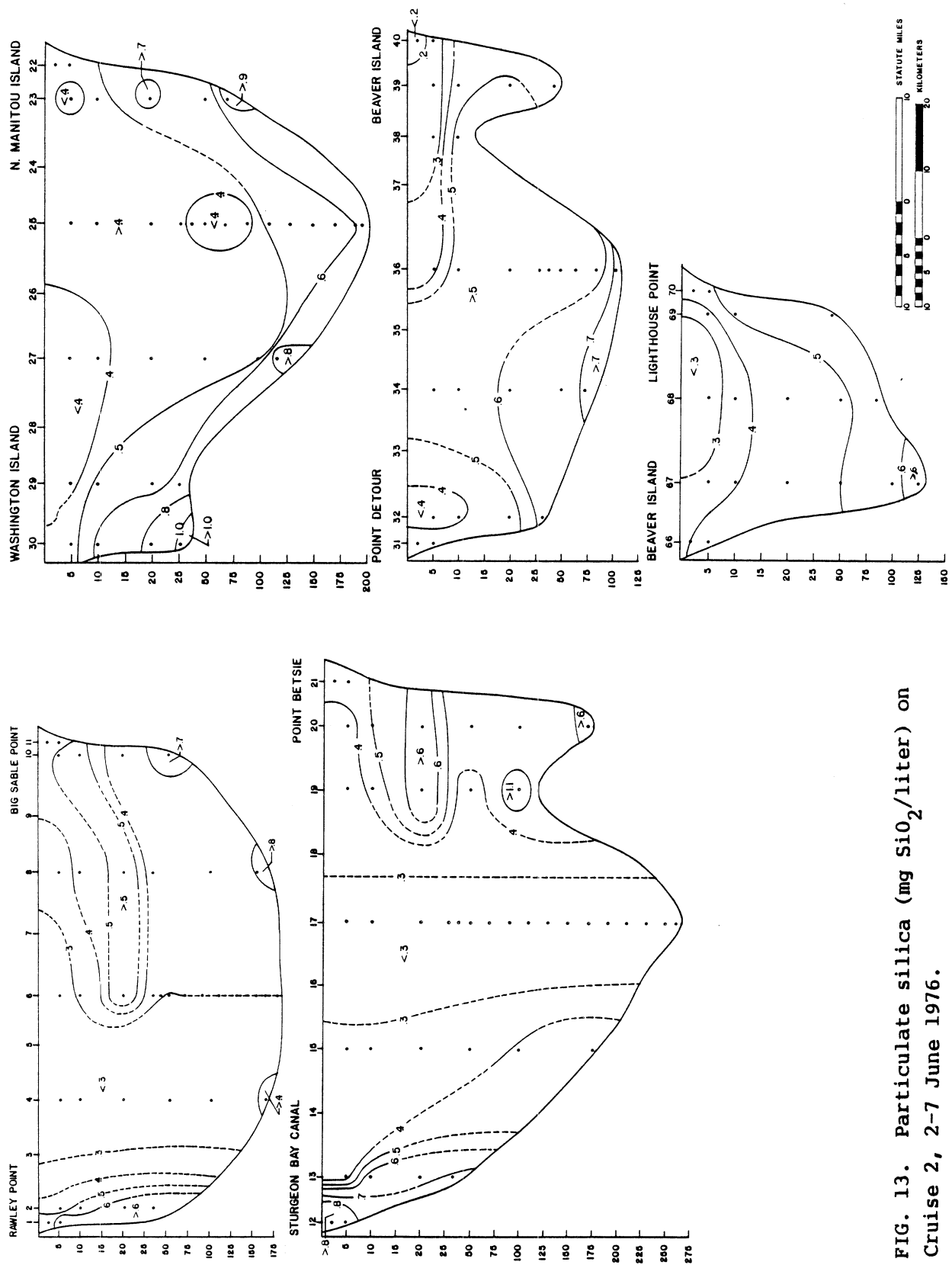
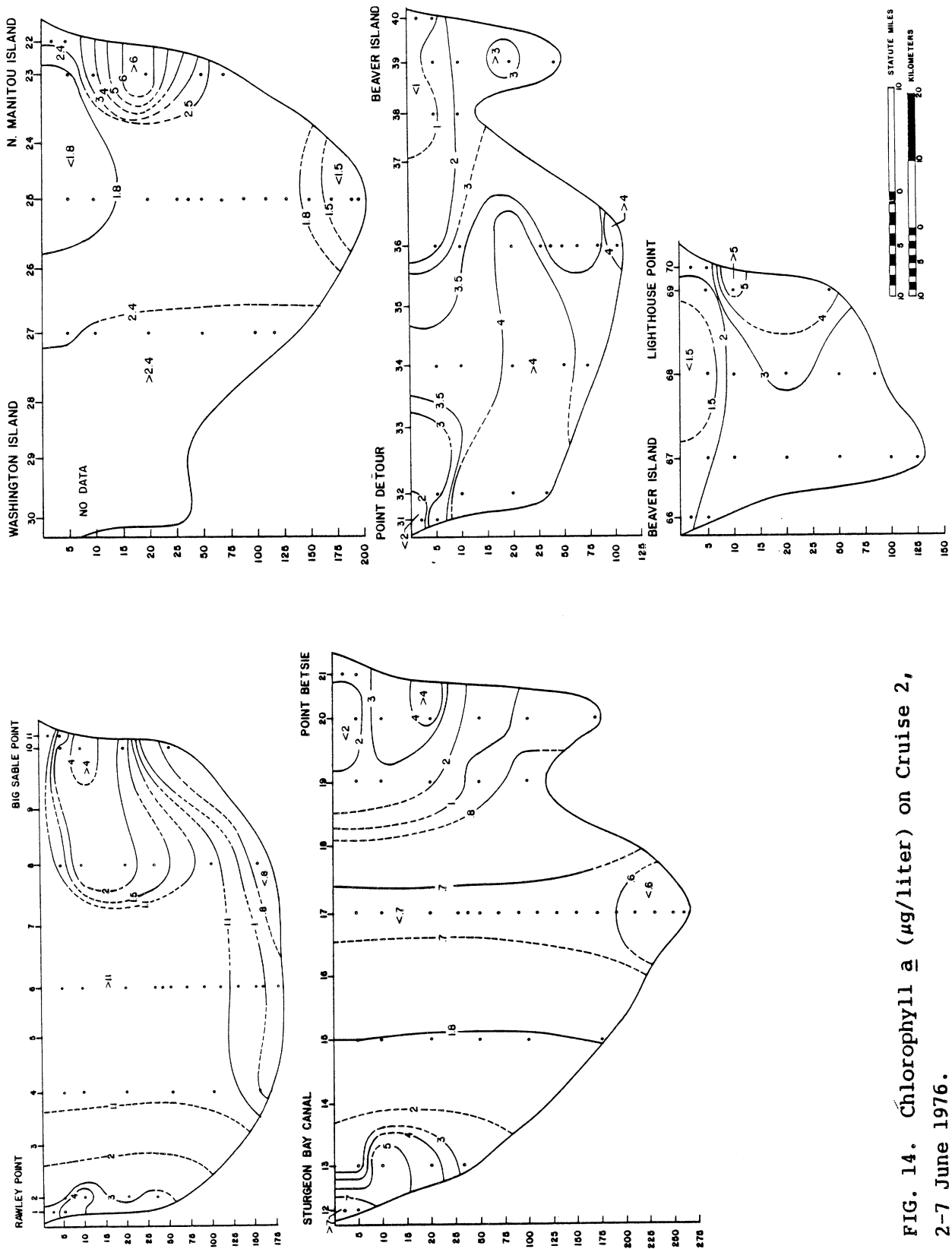


FIG. 13. Particulate silica (mg SiO₂/liter) on Cruise 2, 2-7 June 1976.



isopleth pattern was disrupted slightly by the presence of the subsurface chlorophyll a maximum. Like particulate silica the largest concentrations of chlorophyll a, >4 to >6 $\mu\text{g/liter}$, were found at subsurface depths ranging from 10 to 20 m. Values for chlorophyll a differed from those for particulate silica in that relative range of values for chlorophyll a was greater.

Summary

On the June cruise the thermal bar was well developed in the four east-west transects with midlake temperatures being less than 4.5°C (Fig. 9). Waters were thermally stratified at the nearshore stations on these transects and weakly stratified over the entire Beaver Island transect. Values for pH were largest at the nearshore stations ranging from 8.5 to 8.6 and decreased to <8.3 in the deep waters of the offshore stations.

Distributions of nitrate and silica were related to the thermal regime. Largest concentrations of both nutrients were found at the deep isothermal stations where nitrate concentrations ranged from 0.24 to 0.26 mg/liter (Fig. 11), and silica concentrations ranged from 0.9 to 1.1 mg/liter (Fig. 12). On the three southernmost transects, concentrations of nitrate and silica were lower on the western than on the eastern sides of the transects. This structure also was present in April data. Nitrate concentrations at Stations 2 and 30 were <0.08 and <0.10 mg/liter, indicating extreme depletion from phytoplankton growth in relation to offshore concentrations of 0.24 to 0.26 mg/liter. Silica concentrations at the western stations were <0.1 mg/liter which would severely limit diatom growth.

Particulate silica and chlorophyll a had similar distributions on the three southernmost transects in that there were subsurface maxima in

concentrations at the eastern ends and in that vertical isopleths were present at the western ends. Lowest concentrations of particulate silica and chlorophyll a were found at the midlake stations on these transects. Particulate silica concentrations were as small as 0.3 mg/liter compared to maximum concentrations in the upper 25 m that exceeded 0.8 mg/liter (Fig. 13).

Greatest chlorophyll a concentrations were found at stations near shore between depths of 10 and 20 m where concentrations as large as 6 μ g/liter were found (Fig. 14). These concentrations were much greater than the smallest concentrations (<0.7 μ g/liter) found throughout the water column at Station 17 on the Point Betsie transect.

CRUISE 3, 10-17 JULY

Water Temperature

In July strong thermal stratification was present on every transect with surface temperatures ranging from 14 to 18°C, and hypolimnetic temperatures being <5°C (Fig. 15). The epilimnion was 10 to 15 m deep, except along the eastern shore where there was upwelling on the two southernmost transects. Partly because of upwelling, the epilimnion tended to be deeper on the west side of the lake than on the east side. The resulting thermocline tilt was particularly obvious on the Beaver Island transect where the 14°C isotherm was at 25 m at Station 32 in contrast to Station 40 on the east end of the transect where the 14°C isotherm was at 3 m.

There was no simple thermal structures in the epilimnetic waters on any transect. On the Point Sable transect a well defined, 10- to 15-m epilimnion was found with 4 to 17°C temperatures, except at the nearshore stations on the eastern side where deep waters were being upwelled (Fig. 15). The most complex thermal structure was found on the Point Betsie transect where surface temperatures ranged from 14 to 18°C and upwelling occurred at Station 21. However, the distinctive feature on this transect was the "cold core" of water at Station 17 which was characterized by the presence of the 14°C isotherm at the surface.

Hydrogen Ion Concentration

The spatial distribution of pH in July was related to thermal structure. In the epilimnion pH was generally >8.6, ranging to nearly 8.8 on some transects (Fig. 16). The pH in the hypolimnion generally was <8.3 on the

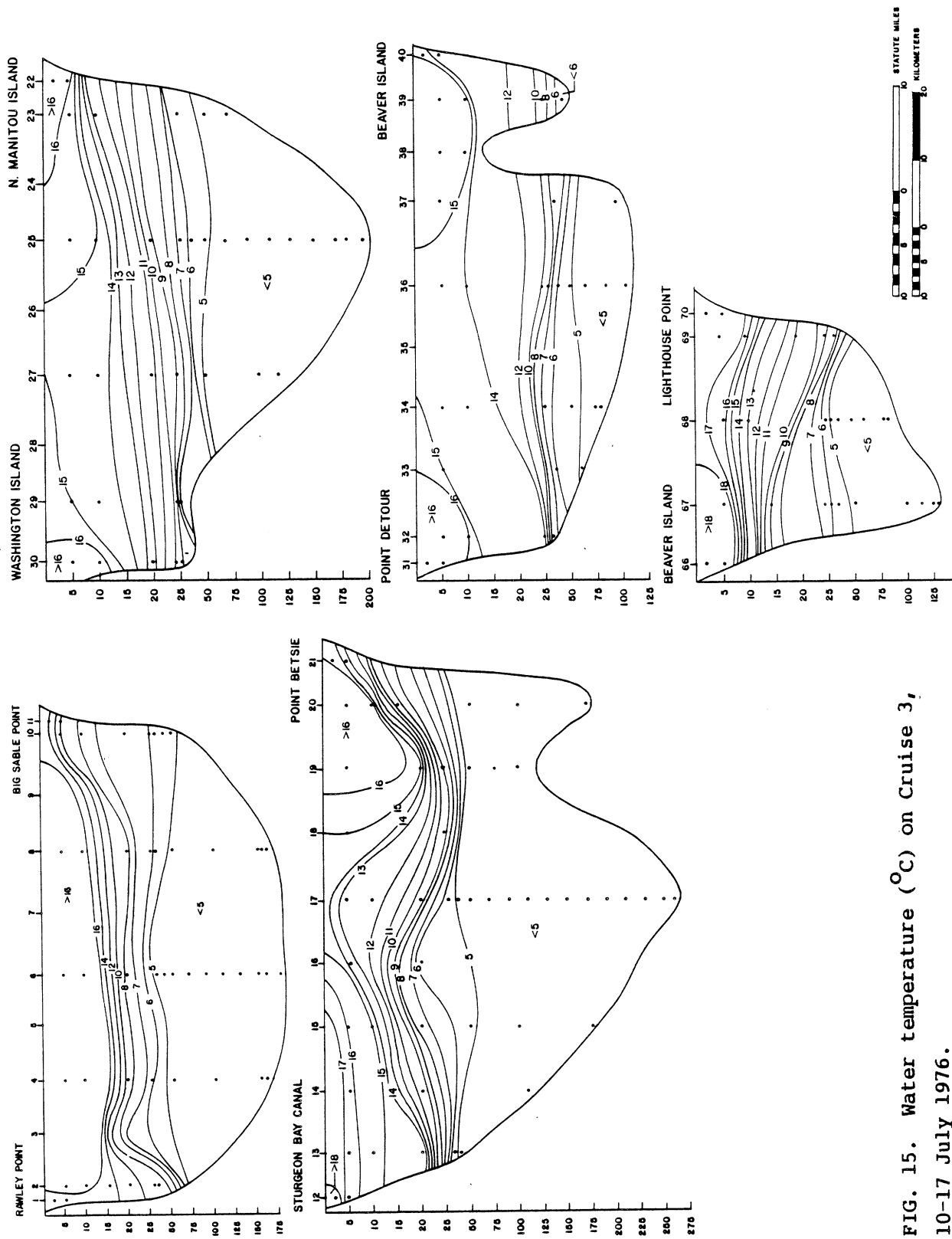


FIG. 15. Water temperature ($^{\circ}\text{C}$) on Cruise 3, 10-17 July 1976.

three deep transects except the Point Sable transect where values were generally <8.4 with values <8.3 being found only in samples collected near the bottom.

The pH values for the Grand Traverse Bay transect were smaller than those at all stations on the other four transects. Values for pH on the transect appeared to be 0.2 to 0.3 pH units smaller than on the other transects. The very low values of pH noted at Station 70 can probably be attributed to a problem with pH electrodes that had not equilibrated after the routine daily standardization.

Nitrate Nitrogen

Spatial patterns of nitrate in July were related to thermal structure. Epilimnetic concentrations generally ranged from 0.11 to 0.16 mg/liter (Fig. 17). Larger concentrations, 0.16 to 0.19 mg/liter, were found in the areas of weak upwelling along the east sides of Big Sable Point and Point Betsie transects and in midlake "cold core" water at Station 17. Elevated surface nitrate concentrations, 0.18 mg/liter, at the deepest coldest station (Station 17) were apparently the result of this "cold core" of water. Epilimnetic concentrations were least on the west sides of Point Betsie and Manitou Island transects, the lowest concentration being <0.11 mg/liter at Station 30 off Death's Door.

Nitrate concentrations in the hypolimnion ranged from 0.20 to 0.28 mg/liter on the three southernmost transects (Fig. 17). Concentrations over most of the volume of the hypolimnion ranged from 0.24 to 0.28 mg/liter with a layer near the bottom being >0.28 mg/liter. Hypolimnetic concentrations in

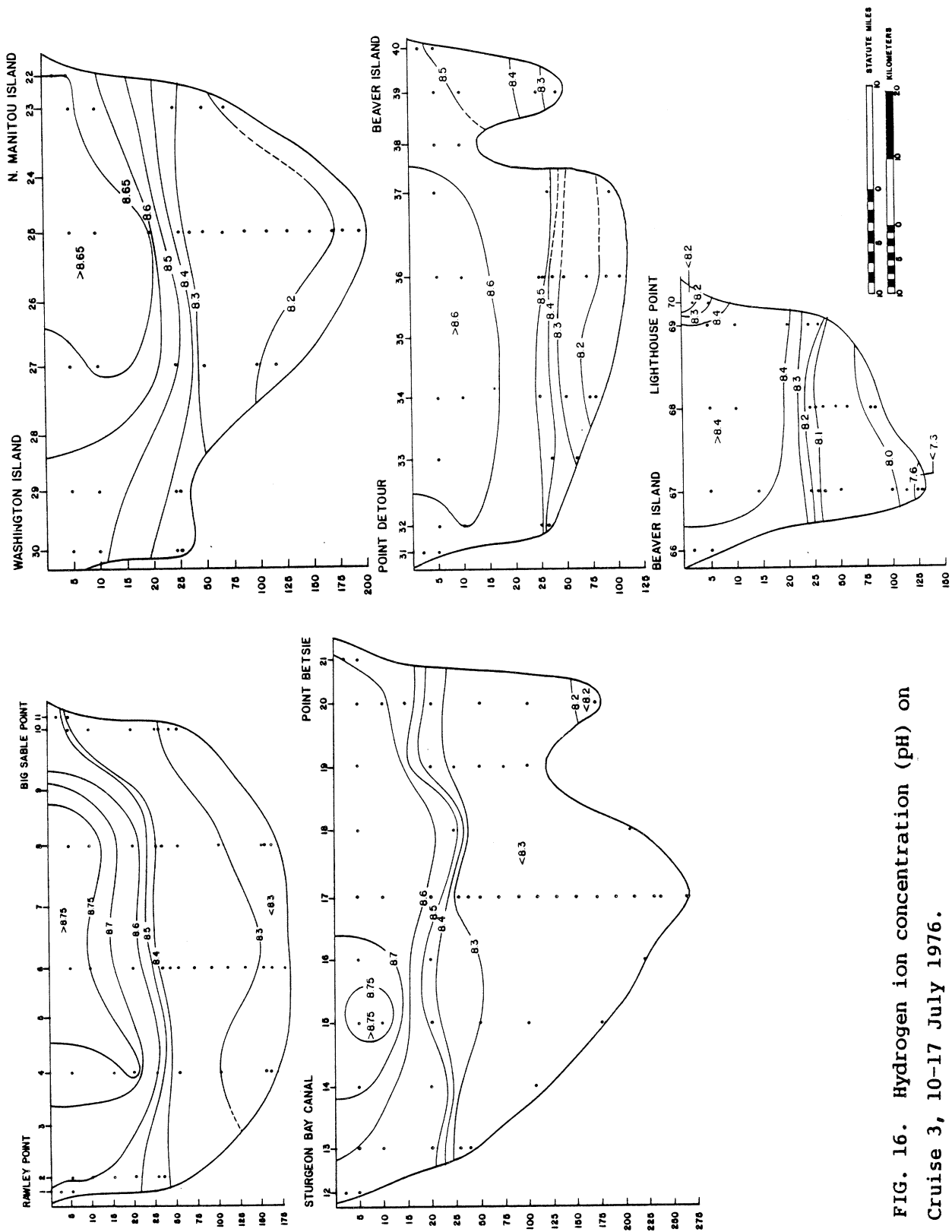


FIG. 16. Hydrogen ion concentration (pH) on Cruise 3, 10-17 July 1976.

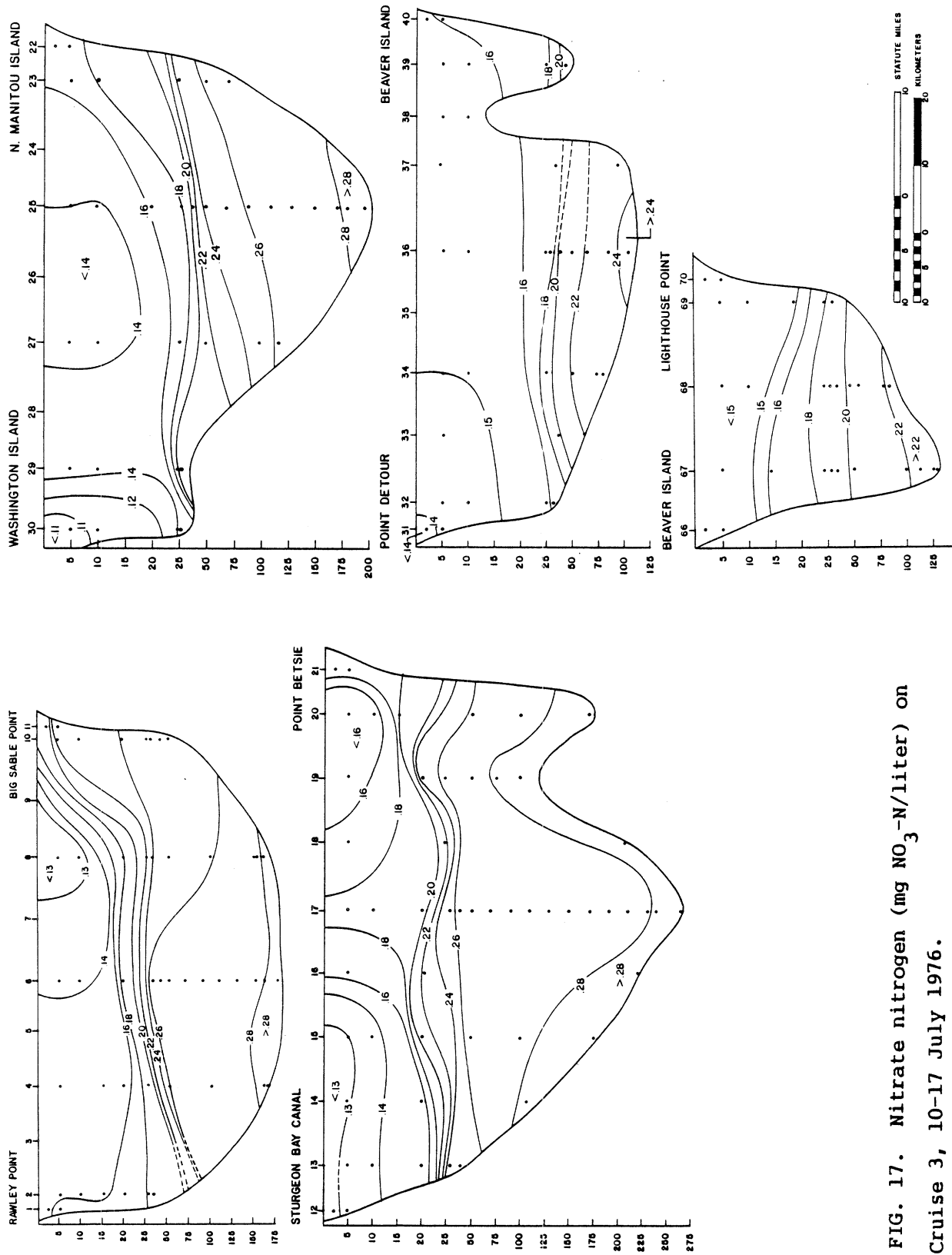


FIG. 17. Nitrate nitrogen (mg NO₃-N/liter) on Cruise 3, 10-17 July 1976.

the lower part of the range, 0.20 to 0.24 mg/liter, were found on the two shallow transects.

Soluble Reactive Silica

In July the influence of thermal stratification on the distribution of silica was very obvious. Silica in epilimnetic waters was depleted relative to concentrations found in the bottom waters, and in general ranged from <0.15 to <0.3 mg/liter over most of the epilimnion (Fig. 18). Silica values along the west shore appeared to be smaller than those on the east shore, an effect that probably resulted from upwelling of silica-rich waters along the east shore. The distribution of silica on the Big Sable Point transect represents a classic example of the influence of upwelling on the spatial distribution of variables that are depleted in the epilimnion relative to the hypolimnion. Concentrations >0.3 mg/liter were found in areas of upwelling off Big Sable Point and Point Betsie and in the "cold core" waters at Station 17. The influence of the "cold core" extended to Stations 16 and 18 where epilimnetic silica values ranged from 0.5 to 0.6 mg/liter.

Silica concentrations in the hypolimnion were greater on the three southernmost transects than on the remaining two shallow transects. On the deep transects concentrations ranged generally from 0.7 to 1.0 mg/liter at depths below 50 m, whereas smaller concentrations, <0.6 mg/liter, were generally found on the shallower Beaver Island and Grand Traverse Bay transects (Fig. 18). The largest concentrations occurred in near-bottom samples and ranged from 1.3-1.8 mg/liter.

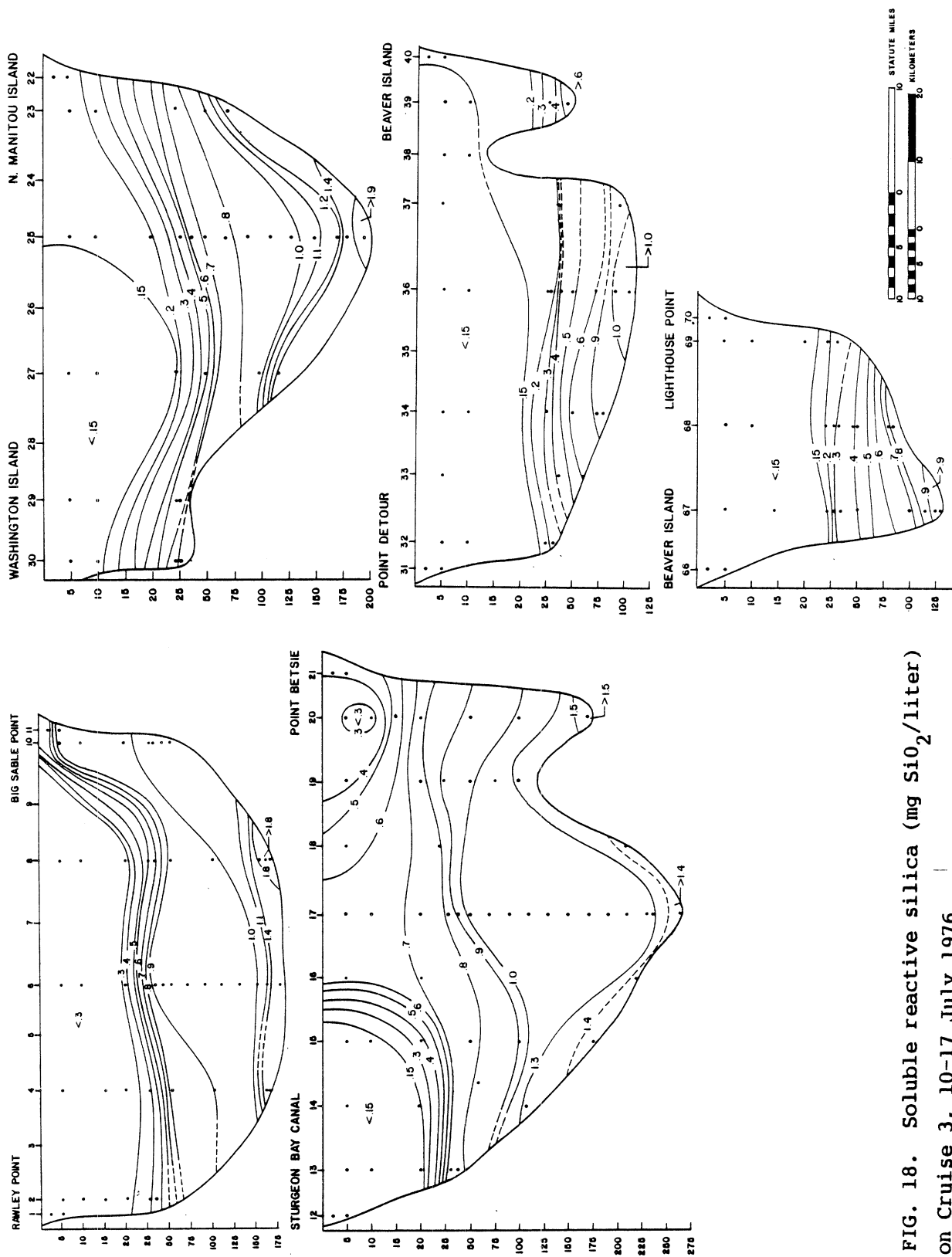


FIG. 18. Soluble reactive silica (mg SiO₂/liter) on Cruise 3, 10-17 July 1976.

Particulate Silica

There were several patterns in the spatial distribution of particulate silica on the July cruise and these patterns were only generally related to thermal structure. First, nearshore concentrations tended to be higher than offshore concentrations (Fig. 19). Second, epilimnetic concentrations at midlake tended to be smaller than concentrations at deeper depths in the water column. Third, on the Big Sable Point and Grand Traverse Bay transects there was a mid-depth concentration maximum, a pattern that was also evident at individual stations on some of the other transects. Finally, largest concentrations of particulate silica were found in near-bottom and bottom samples. Except for bottom and near-bottom samples, particulate silica concentrations were small, ranging generally from 0.2 to 0.6 mg/liter. Some bottom and near-bottom concentrations were larger, ranging from 1.0 to 2.0 mg/liter. The only surface concentrations >1.0 mg/liter occurred at Station 11 where upwelled water influenced chemical characteristics and apparently resulted in greater chlorophyll a concentrations than those found at adjacent stations (Fig. 20).

Chlorophyll a

The most striking feature in the spatial distribution of chlorophyll a in July was the presence of subsurface maxima on all transects. Largest concentrations were below the epilimnion at depths of 20 to 25 m (Fig. 20). Concentration maxima ranged from 3 μ g/liter on the shallow Beaver Island transect to >7 μ g/liter on the Grand Traverse Bay transect.

Epilimnetic chlorophyll a concentrations were generally <2 μ g/liter, with most of the epilimnetic volume being <1.5 μ g/liter (Fig. 20). Concentrations

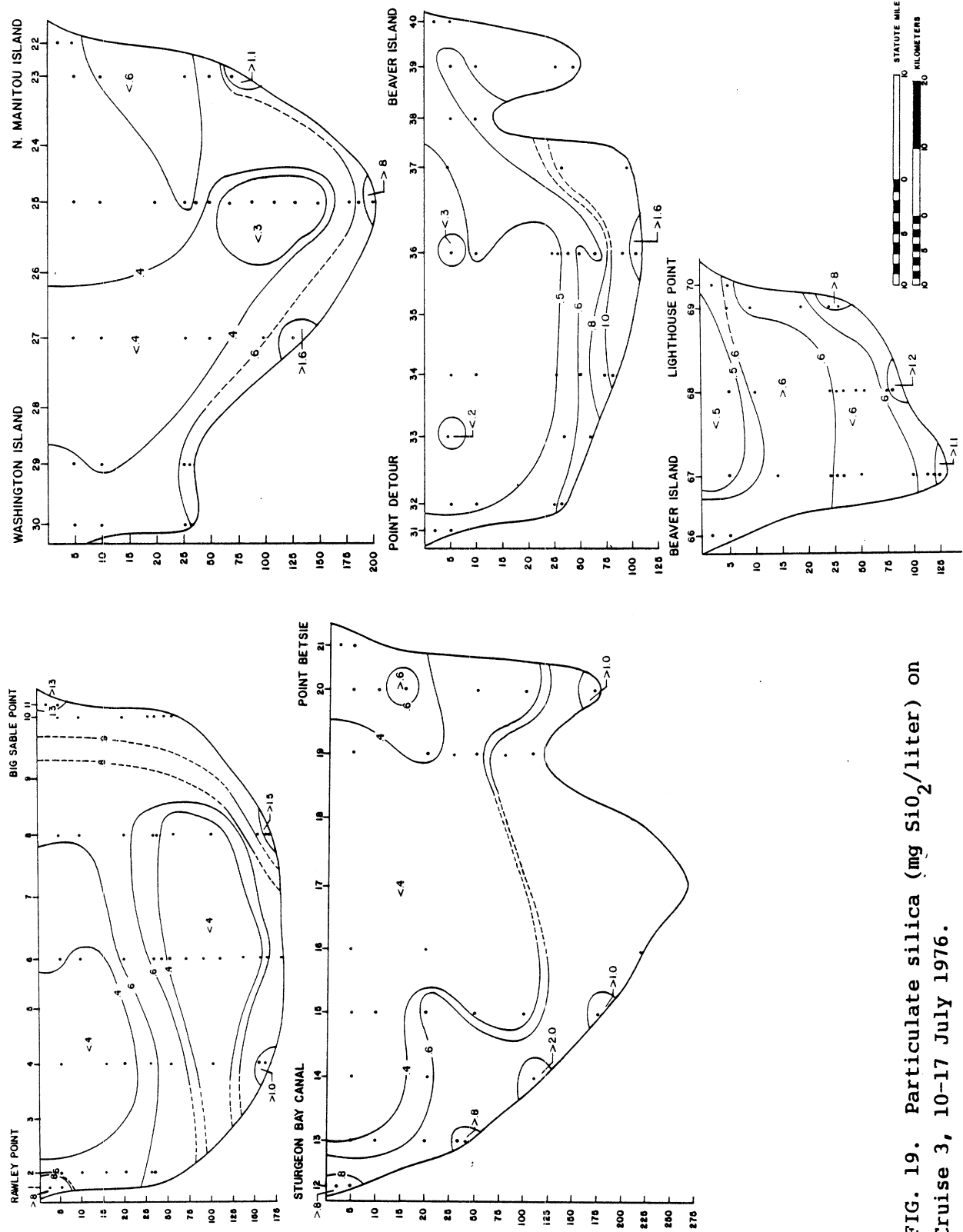


FIG. 19. Particulate silica (mg SiO₂/liter) on Cruise 3, 10-17 July 1976.

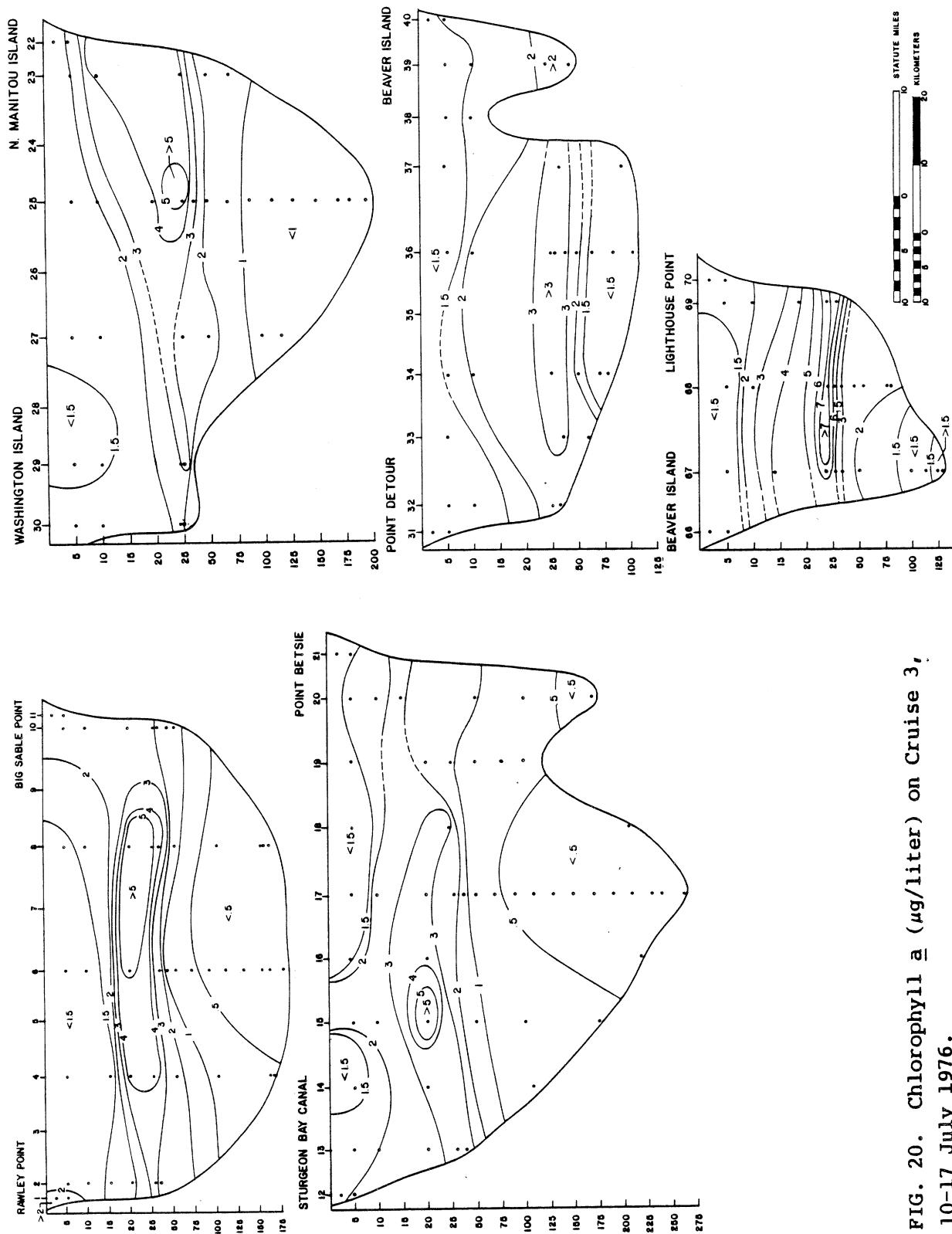


FIG. 20. Chlorophyll a ($\mu\text{g/liter}$) on Cruise 3, 10-17 July 1976.

>2 $\mu\text{g/liter}$ were found at both ends of the Point Sable transect. On the east side of this transect concentrations larger than those at midlake were undoubtedly attributable to upwelling.

Concentrations in hypolimnetic waters were generally <1.5 $\mu\text{g/liter}$ (Fig. 20). Smaller concentrations, <1 $\mu\text{g/liter}$, were found on the three deep southernmost transects with large volumes of the hypolimnion having concentrations <0.5 $\mu\text{g/liter}$. Larger hypolimnetic concentrations, 1 to 2 $\mu\text{g/liter}$, on the Beaver Island and Grand Traverse Bay transects may be related to shallower water depths on these transects which are <100 m.

Summary

Strong thermal stratification was present at all stations in July and surface temperatures ranged from 14 to 18°C (Fig. 15). Epilimnetic depths ranged from 10 to 15 m except where upwelling occurred at stations along the eastern shore. A "cold core" was found at Station 17 where the 14°C isotherm extended to the surface. The spatial distribution of pH was related to thermal structure; epilimnetic values for pH ranged from 8.6 to 8.8 and hypolimnetic values were 8.3 or less (Fig. 16).

Distributions of nitrate and silica were also related to thermal structure. Epilimnetic nitrate concentrations ranged from 0.11 to 0.16 mg/liter with larger concentrations of 0.16 to 0.19 mg/liter being found in upwelled water off Big Sable Point and Point Betsie and in the "cold core" water at Station 17 (Fig. 17). In the hypolimnion, nitrate concentrations ranged from 0.20 to 0.28 mg/liter with concentrations over most of the volume being between 0.24 and 0.28 mg/liter. Silica concentrations in the epilimnion ranged from 0.11 to 0.30 mg/liter except at the stations where upwelled and

"cold core" waters were present (Fig. 18). At these stations (Stations 10, 11, and 17) concentrations were >0.6 mg/liter.

The most striking feature in the distribution of chlorophyll a on the July cruise was the subsurface concentration maximum found between 20 and 30 m in the upper part of the hypolimnion. Concentrations in this subsurface layer ranged from 3 to 7 μ g/liter (Fig. 20) in comparison with surface concentrations that were generally <1.5 or 2 μ g/liter. The spatial distribution of particulate silica was complex and only generally related to thermal structure (Fig. 19).

CRUISE 4, 12-17 AUGUST

Water Temperature

Thermal stratification in August was well developed and more uniform than in July. Epilimnetic temperatures generally ranged from 18 to 20°C (Fig. 21). Compared to conditions in July, when the water column was also thermally stratified, temperatures had increased slightly and the depth of the epilimnion had increased about 5 m to depths ranging from 15 to 20 m. Epilimnetic temperatures over most of the transects were quite uniform. On the two southernmost transects weak upwelling was noted along the eastern shore off Big Sable Point and Point Betsie. The effect of wind stress on thermocline depth on the shore opposite the site of upwelling is particularly evident from the 25-m deep epilimnion off Rawley Point. Even where there was no evidence for upwelling, the nearshore waters tended to be slightly cooler than the offshore waters except for stations off North Manitou Island and off Lighthouse Point on the Grand Traverse Bay transect.

Minimum hypolimnetic temperatures were generally <5°C (Fig. 21). The exception was slightly warmer temperatures on the shallow Beaver Island transect which were <6°C in the hypolimnion.

Hydrogen Ion Concentration

Spatial distributions of hydrogen ion concentration in August closely paralleled temperature distribution, and the patterns were relatively simple with the exception of stations off Death's Door. Surface water flowing out of Green Bay through Death's Door at Station 30 apparently had a pH >8.7 but below this water, at depths >15 m, pH values dropped to <8.4 (Fig. 22).

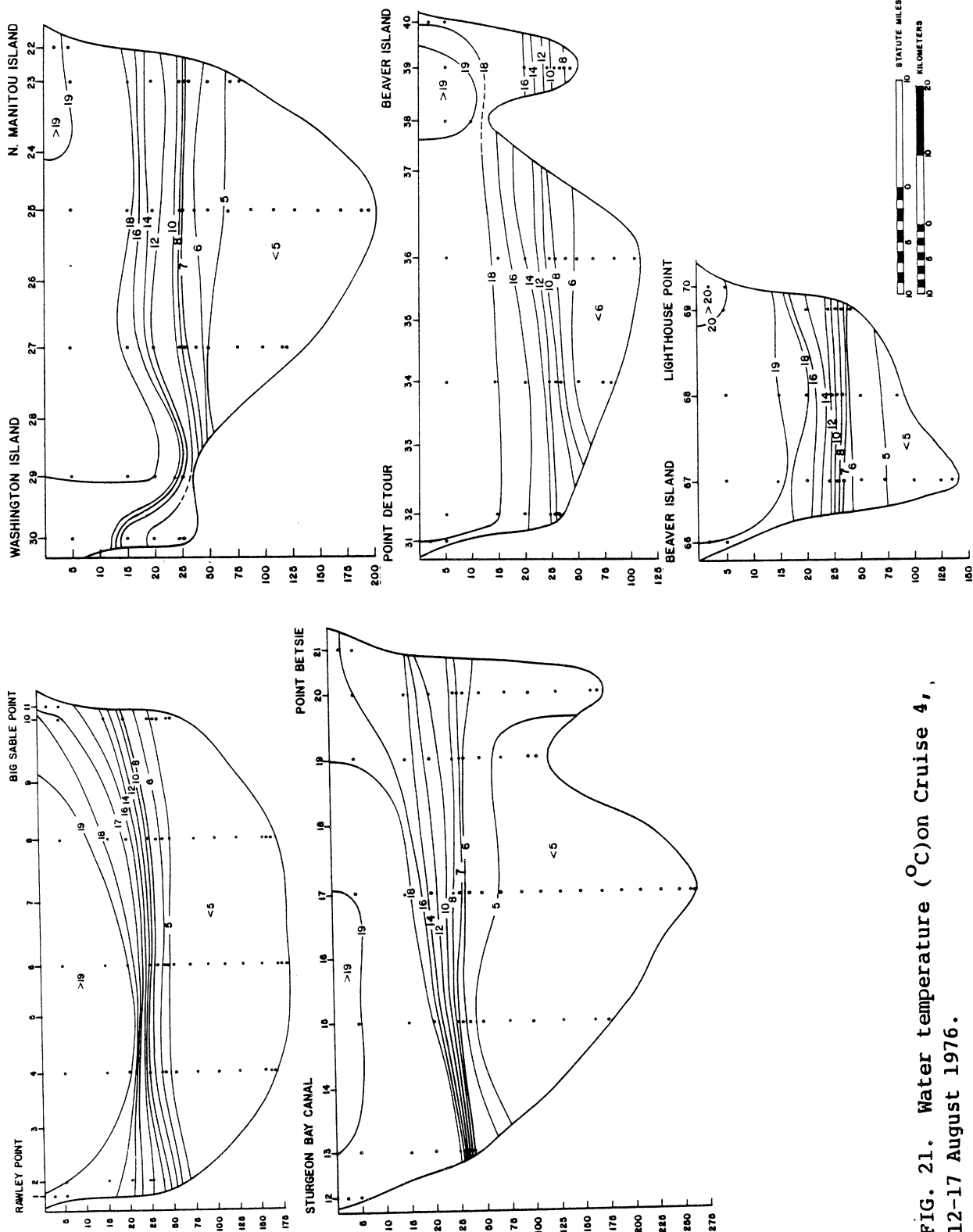


FIG. 21. Water temperature ($^{\circ}\text{C}$) on Cruise 4, 12-17 August 1976.

In the epilimnion all pH values were >8.5 . Values larger than 8.6 were restricted to nearshore stations generally and to 15- to 25-m depths on some transects. A large part of the epilimnion on the shallow Beaver Island transect also had pH values >8.6 . Why pH values <8.5 were found at Station 29 on the North Manitou Island transect is not readily explainable; possibly the cause was entrainment of hypolimnetic water with low pH from Station 30. In the hypolimnion values for pH were <8.4 with the pH for large volumes of the hypolimnion ranging from 8.2 to 8.3 (Fig. 22).

Nitrate Nitrogen

Spatial distributions of nitrate in August were generally related to thermal structure. Epilimnetic concentrations were 0.16 mg/liter or less, with the exception of values as large as 0.20 mg/liter at Station 21 where weak upwelling occurred (Fig. 23). Over much of the epilimnion, concentrations were <0.14 mg/liter but were even smaller, <0.12 mg/liter, on the west side of the three southernmost transects. The lowest concentration on these transects, <0.10 mg/liter at Station 30, was attributed to water from Green Bay flowing out of Death's Door. This low nitrate concentration in the epilimnion at Station 30 contrasted with an intrusion of cold water with concentrations >0.18 mg/liter at depths >15 m.

Hypolimnetic concentrations were generally from 0.26 to 0.27 mg/liter on the three southernmost transects with larger concentrations, >0.27 mg/liter, occurring near the bottom (Fig. 23). On the two remaining transects hypolimnetic concentrations were much lower, ranging from 0.18 to 0.22 mg/liter on the Grand Traverse Bay transect and from 0.20 to 0.26 mg/liter on the Beaver Island transect.

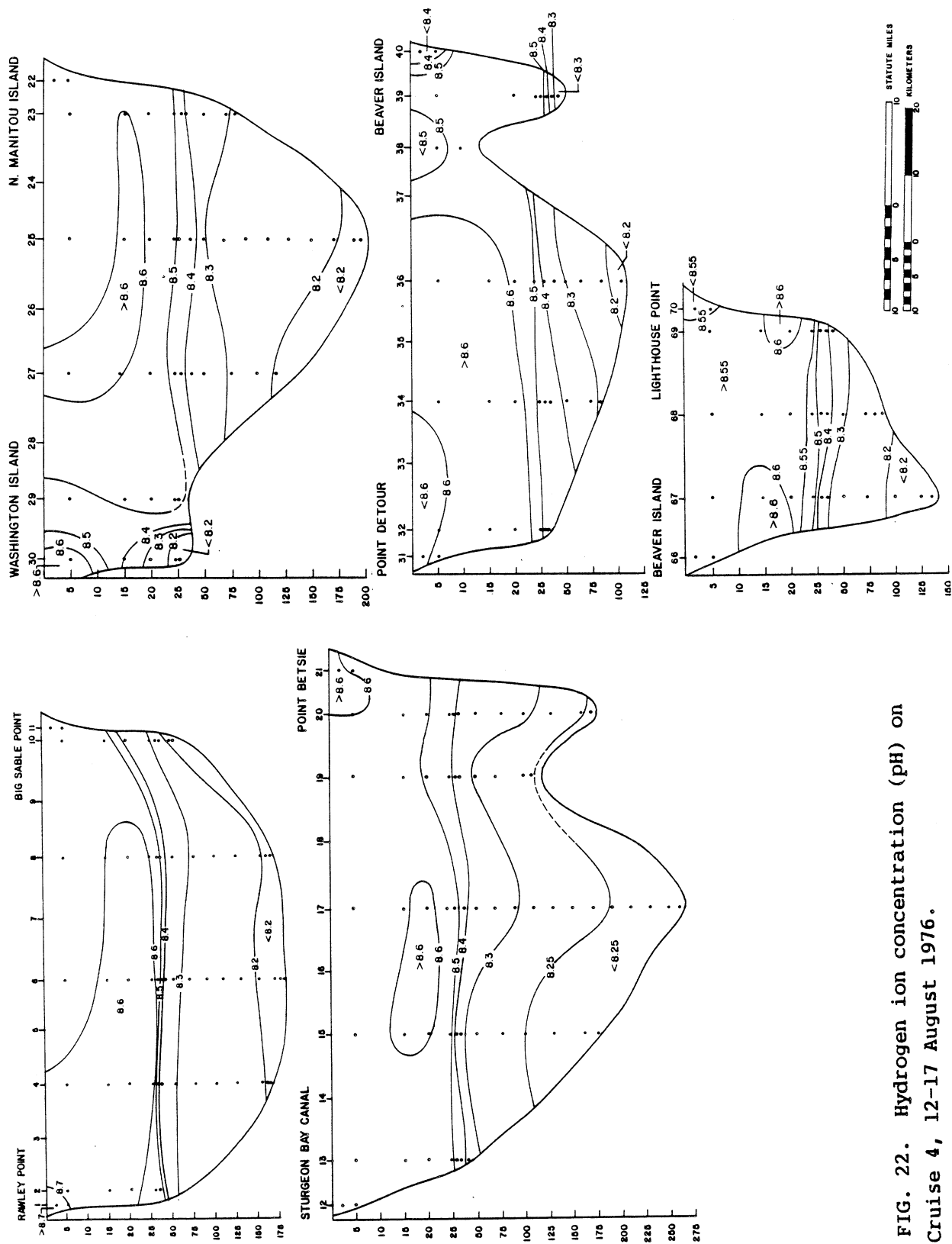


FIG. 22. Hydrogen ion concentration (pH) on Cruise 4, 12-17 August 1976.

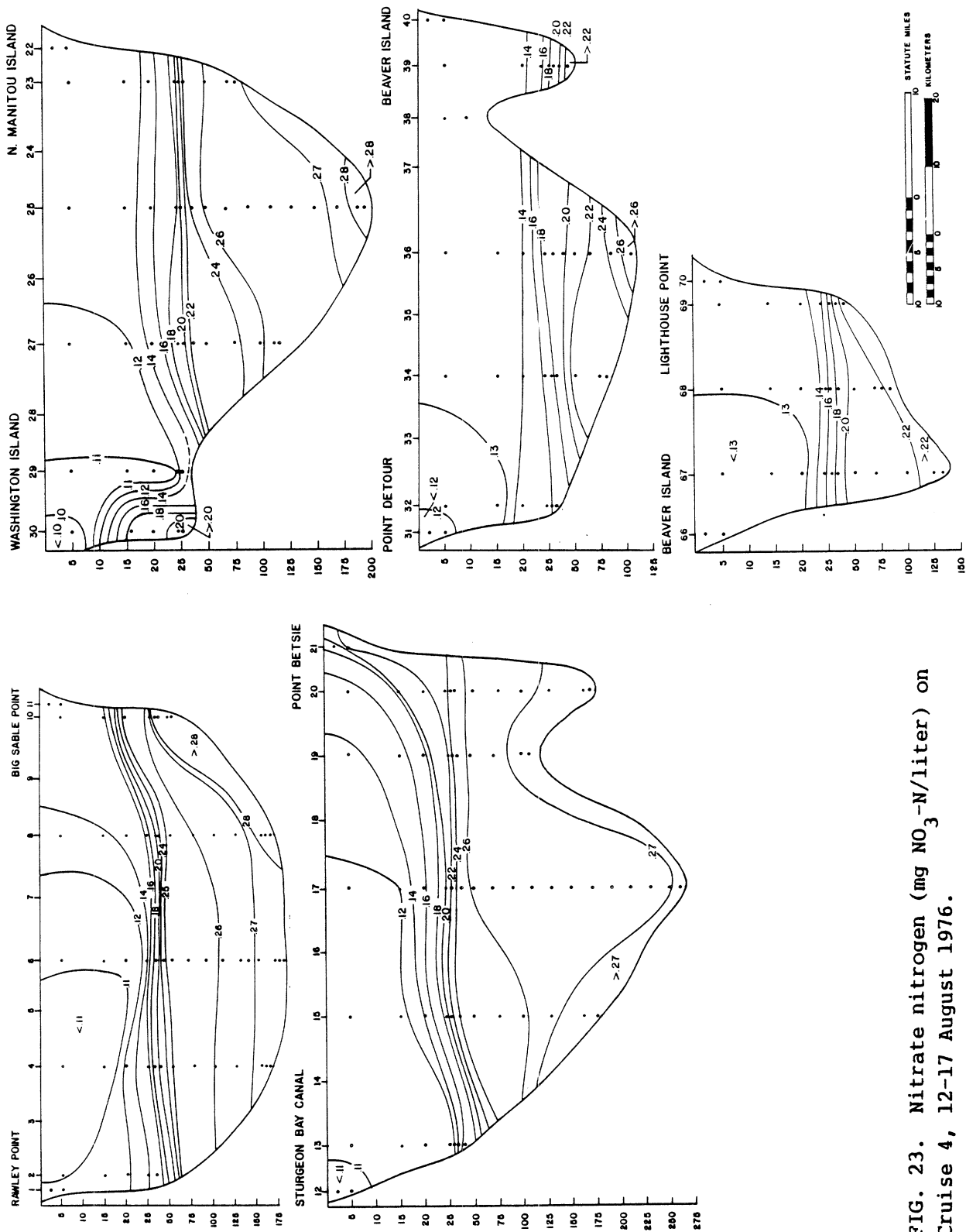


FIG. 23. Nitrate nitrogen (mg NO₃-N/liter) on Cruise 4, 12-17 August 1976.

Soluble Reactive Silica

The spatial distribution of silica in August was strongly related to thermal structure. Epilimnetic silica concentrations were severely depleted relative to concentrations in the hypolimnion. Epilimnetic concentrations were generally <0.3 mg/liter except at Stations 20 and 21 off Point Betsie where upwelling was present (Fig. 24). Much of the epilimnion had silica concentrations <0.2 mg/liter, and subsurface minima <0.15 mg/liter were noted at depths of 15 to 25 m at Stations 29 and 34.

Hypolimnetic concentrations >1 mg/liter were found at depths >50 m at midlake stations on the three deep southernmost transects (Fig. 24). The major exception to this pattern was the intrusion of deep cold water at Station 30 with concentrations >1.2 mg/liter, thus high silica water was observed at the 15-m depth. On the two shallow transects concentrations >1 mg/liter were limited to near-bottom samples and to depths close to the bottom. On the Beaver Island transect and on the other three east-west transects most hypolimnetic concentrations ranged from 0.6 to 1.3 mg/liter. In contrast, concentrations on the Grand Traverse Bay transect were generally <1 mg/liter.

Silica concentrations were greatest in near-bottom samples and at depths close to the bottom. Concentrations for these samples ranged from 1.4 to >2.5 mg/liter (Fig. 24). In general, the largest concentrations were found at the deepest stations on each transect.

Particulate Silica

The distribution of particulate silica in August was obviously not strongly related to the thermal structure. In epilimnetic waters highest

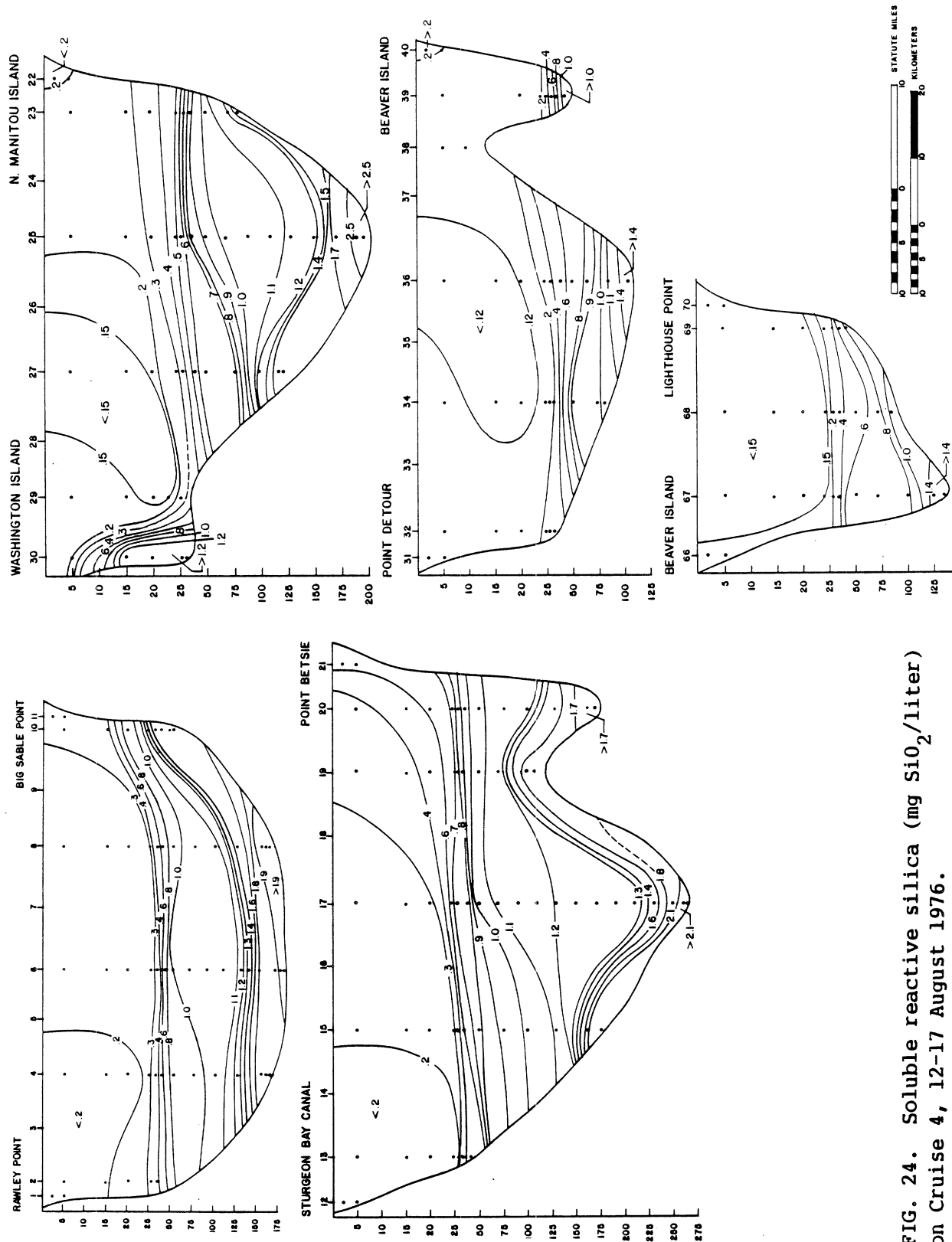


FIG. 24. Soluble reactive silica (mg SiO₂/liter) on Cruise 4, 12-17 August 1976.

concentrations were found near shore, particularly on the west side of the lake, with lowest concentrations being observed at mid lake on all transects. Minimum concentrations in the epilimnion ranged from <0.2 to <0.3 mg/liter (Fig. 25). Nearshore concentrations ranged from 0.6 to 0.8 mg/liter on the western sides of the three southernmost transects and were >0.4 mg/liter at Station 21 where upwelling occurred.

Maxima in particulate silica concentration were noted at some stations where values >0.4 mg/liter were found at depths from 25 to 50 m (Fig. 25). On the three southernmost transects a subsurface minimum of <0.3 mg/liter was found in the hypolimnion at depths ranging from 75 m to as deep as 225 m at Station 17. The largest concentrations were found in the deepest samples, with concentrations being >0.6 mg/liter for samples close to the bottom and >1.0 mg/liter in near-bottom samples.

Chlorophyll a

The most prominent feature in the distribution of chlorophyll a during August was the presence of a subsurface chlorophyll maximum similar to that observed in July. Concentrations in this layer were smaller than those observed in July and generally ranged from 2 to 3 $\mu\text{g/liter}$ (Fig. 26). The largest concentration in August, >4 $\mu\text{g/liter}$, was found at Station 20 on the Point Betsie transect.

Concentrations in the epilimnion generally ranged from 1.0 to 1.5 $\mu\text{g/liter}$ with greater concentrations being restricted to nearshore stations (Fig. 26). Values >1.5 $\mu\text{g/liter}$ were also found at Station 29 where physical and chemical conditions were atypical.

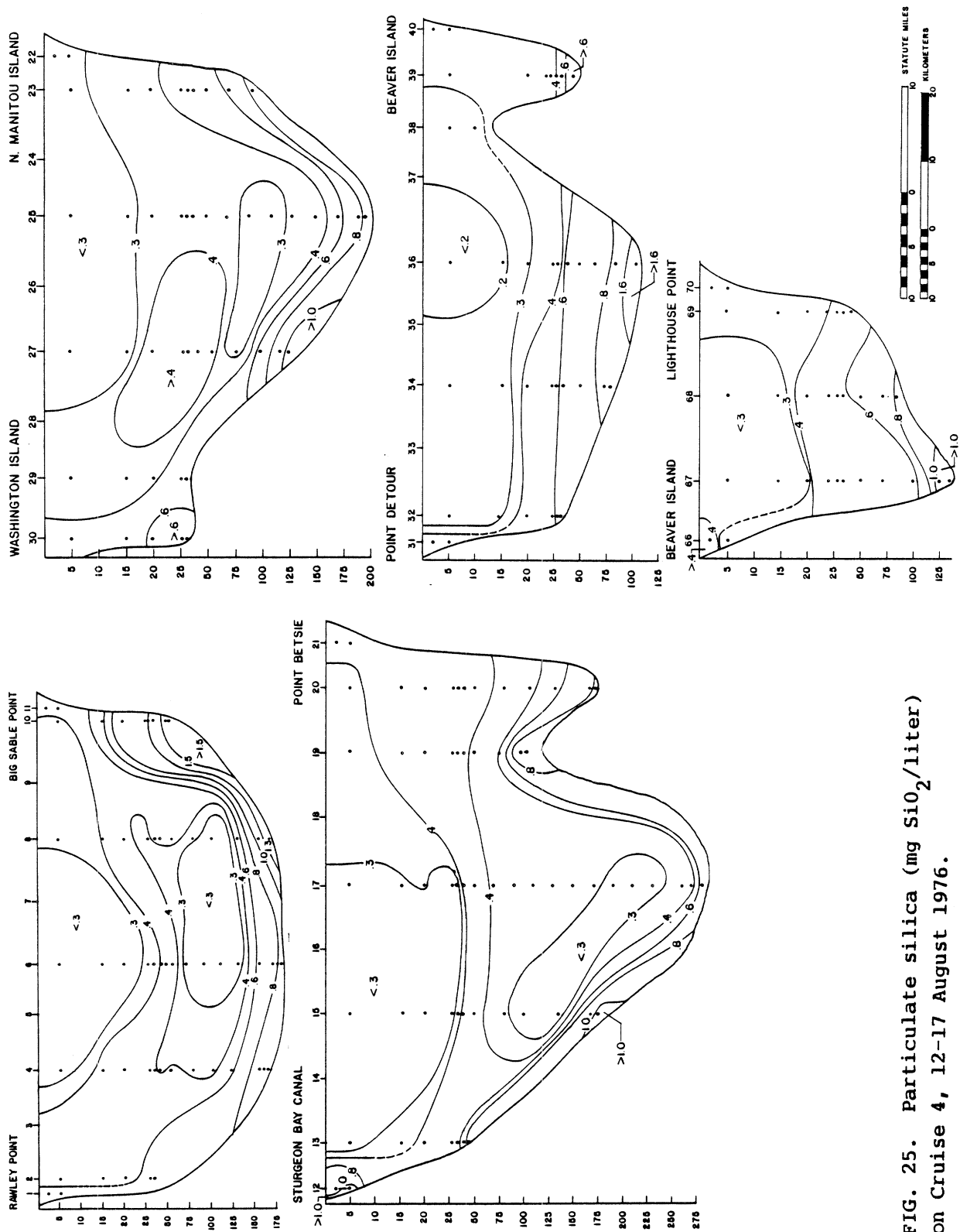


FIG. 25. Particulate silica (mg SiO₂/liter) on Cruise 4, 12-17 August 1976.

Hypolimnetic concentrations on the three southernmost transects were generally $<1 \mu\text{g/liter}$ except in the layer immediately below the subsurface chlorophyll maximum where concentrations ranged from 1 to $2 \mu\text{g/liter}$ (Fig. 26). Most of the volume of the hypolimnion on these deep transects had chlorophyll a concentrations $<0.6 \mu\text{g/liter}$ with concentrations being $<0.2 \mu\text{g/liter}$ below 150 m at Station 17, the deepest station. On the shallow Beaver Island and Grand Traverse Bay transects chlorophyll a concentrations in the hypolimnion were $>1 \mu\text{g/liter}$.

Summary

In August, thermal stratification was well developed and more uniform than in July. Epilimnetic temperatures ranged from 18 to 20°C and the depth of the epilimnion was about 15 to 20 m (Fig. 21). Spatial distributions of pH were generally related to water temperature. In the epilimnion, pH ranged from 8.5 to 8.6 (Fig. 22). However, maximum values (>8.6) were found at depths ranging from 15 to 25 m as the result of increased growth of phytoplankton and large standing crops of chlorophyll a (Fig. 26) at these depths.

In August, water at Station 30 had distinct physical, chemical, and biological characteristics. These results indicate that water from Green Bay was being transported to Lake Michigan through Death's Door. These anomalous distributions were particularly evident for pH (Fig. 22), nitrate (Fig. 23), silica (Fig. 24), and chlorophyll a (Fig. 26).

Nitrate and silica concentrations were related to thermal structures. Epilimnetic concentrations of nitrate were generally from 0.11 to 0.14 mg/liter in comparison to hypolimnetic concentrations that were as large as 0.26

to 0.27 mg/liter (Fig. 23). Although epilimnetic nitrogen concentrations had decreased since July, epilimnetic silica concentrations remained at low levels ranging from 0.1 to 0.3 mg/liter (Fig. 24). Epilimnetic concentrations of both nutrients were lowest on the west end of the three southernmost transects. Upwelling apparently increased surface concentrations at Stations 20 and 21 on the Point Betsie transect.

The subsurface chlorophyll a maximum found in July was present, although concentrations in August were smaller and the layer was less distinct than in July. In August concentrations were generally between 2 and 3 $\mu\text{g/liter}$ with only a few samples exceeding 4 $\mu\text{g/liter}$ (Fig. 26).

The spatial distribution of particulate silica was not related to thermal structure. In the surface waters, concentrations were greatest on the west ends of the three southernmost deep transects and in the offshore waters a mid-depth maximum in concentration was found at some stations at depths ranging from 25 to 50 m (Fig. 25).

CRUISE 5, 7-13 OCTOBER

Water Temperature

Epilimnetic water temperatures on the October cruise were less variable than those for stratified periods sampled on the July and August cruises. Temperatures over the epilimnion on all transects only ranged from 12 to 14°C and the epilimnetic depth generally ranged from 25 to 30 m (Fig. 27). Hypolimnetic temperatures were generally <5°C except on the Grand Traverse Bay transect where temperatures were <6°C.

The only atypical temperature distribution was that present between Stations 29 and 30 where isotherms were vertical. Apparently this resulted from water >13°C that was flowing out of Death's Door from Green Bay and the presence of water slightly colder than 12°C throughout the epilimnion at Station 29 (Fig. 27).

Hydrogen Ion Concentration

In general, the spatial distribution of pH in October was related to water temperature. Epilimnetic values generally were >8.5 except at Station 30 where water from Death's Door had a pH <8.5 (Fig. 28). There were also areas of pH <8.5 off North Manitou Island and in most of the epilimnion on the Grand Traverse Bay transect. In the hypolimnion, values for pH in October were generally <8.3 and in the deeper waters decreased to <8.25.

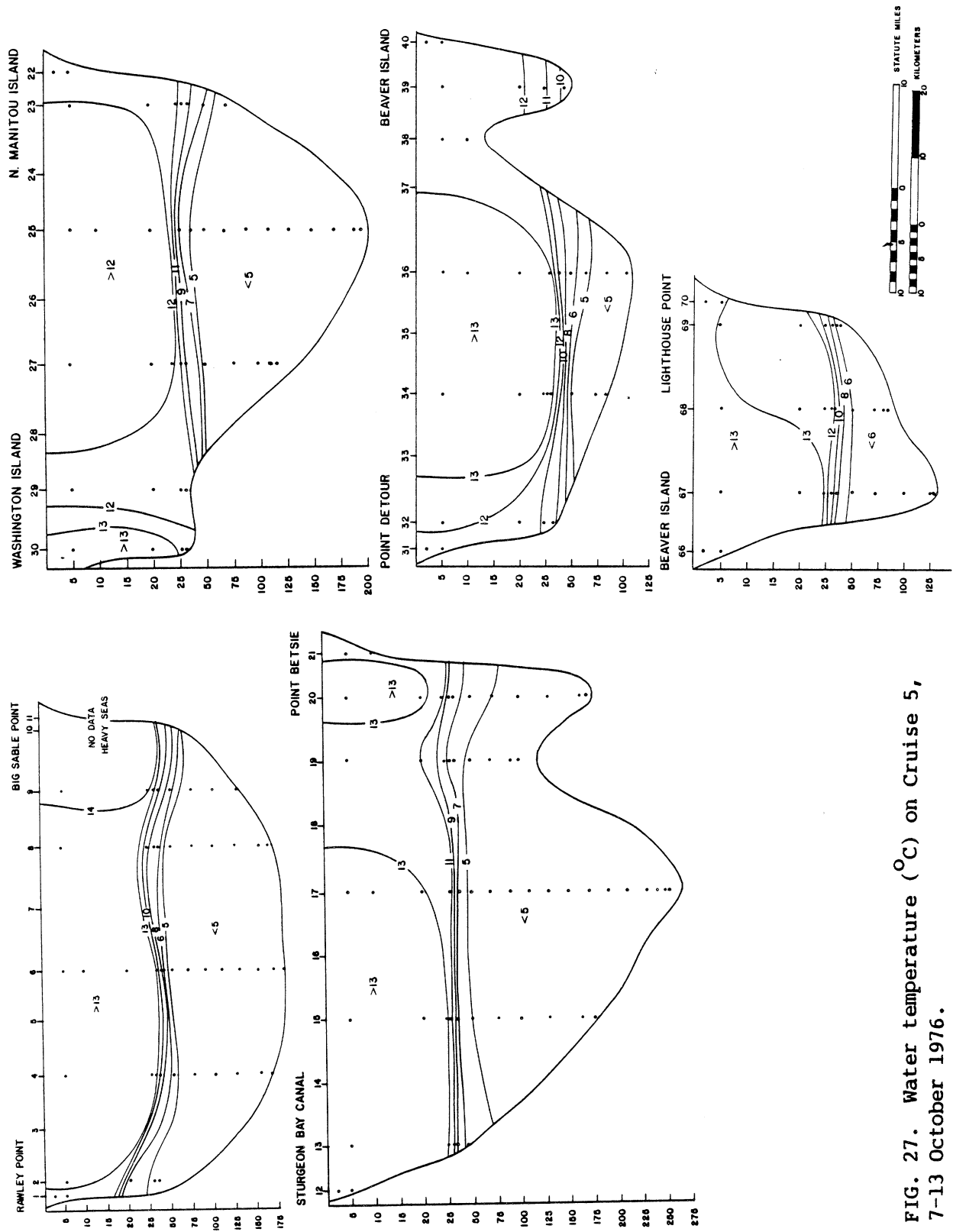


FIG. 27. Water temperature ($^{\circ}\text{C}$) on Cruise 5, 7-13 October 1976.

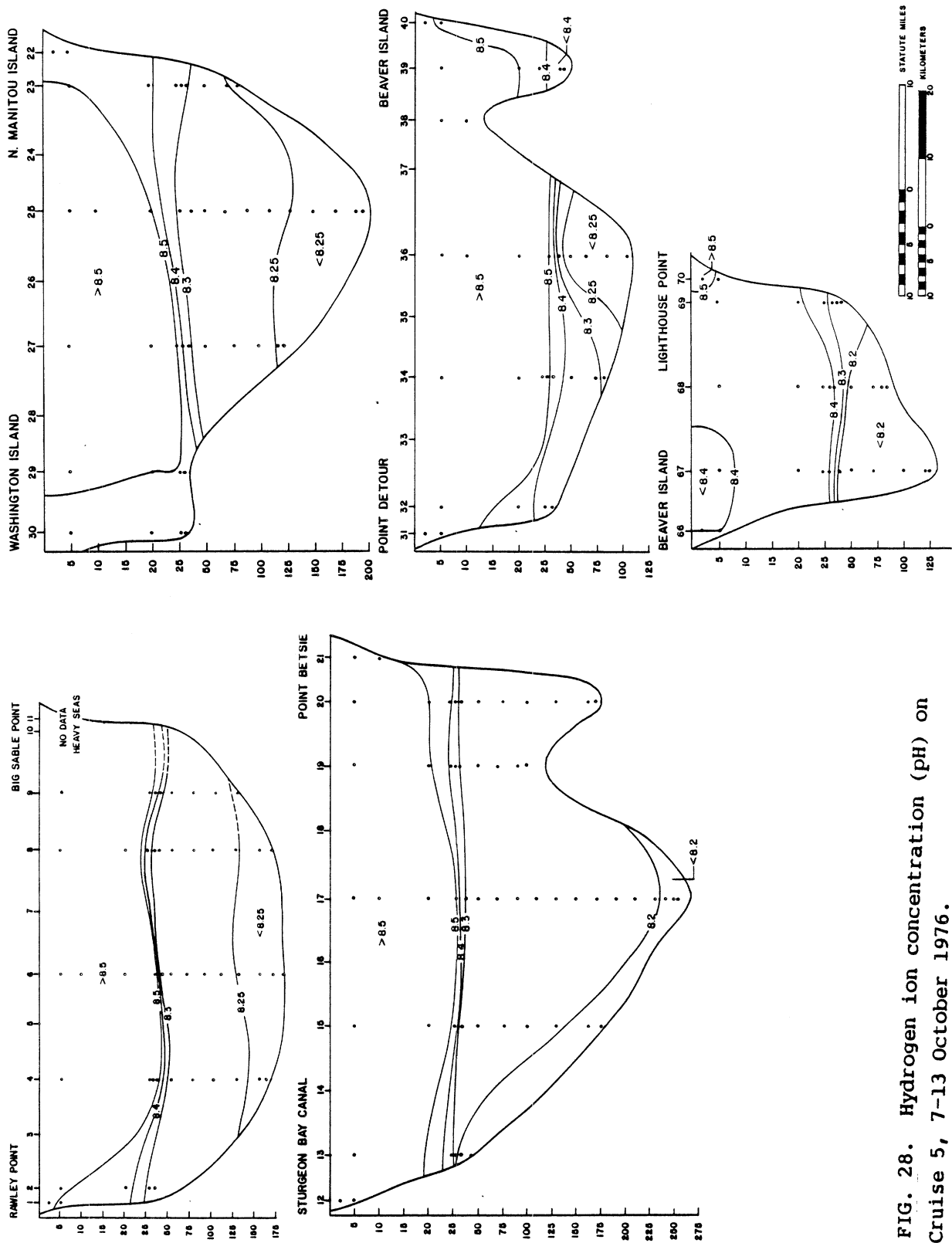


FIG. 28. Hydrogen ion concentration (pH) on Cruise 5, 7-13 October 1976.

Nitrate Nitrogen

Spatial patterns in the epilimnetic distribution of nitrate during October were more complex than those for temperature. Concentrations in the epilimnion were generally <0.16 mg/liter with the largest concentrations, 0.15 to 0.16 mg/liter, occurring on the eastern ends of the two northern transects (Fig. 29). Concentrations over most of the epilimnetic volume ranged from 0.14 to 0.15 mg/liter. Lower values, <0.12 mg/liter, were found near shore at Station 12 near the entrance to the Sturgeon Bay Ship Canal; and the lowest values, <0.11 mg/liter, were found at Station 30 near Death's Door. The low nitrate water flowing out of Death's Door that was measured at Station 30 obviously affected the spatial pattern of nitrate on this transect and produced vertical isopleths between Stations 29 and 30.

In the hypolimnion, concentrations increased with depth but most of the volume ranged from 0.26 to 0.28 mg/liter (Fig. 29). Values >0.28 mg/liter were found near the bottom on the southernmost transect. On the Grand Traverse Bay transect hypolimnetic values were lower, generally <0.26 mg/liter.

An unusual feature in the spatial distribution of nitrate was noted at Stations 17 and 25 where there was a mid-depth maximum in concentration (Fig. 29). Although not contoured, a similar pattern in distribution was suggested by data collected at other stations. If this distribution is real, it may reflect the effects of hypolimnetic mixing at these deep stations or the results of nitrification of ammonia. Concentrations of ammonia reported under SEASONAL CHANGES were greatest in the metalimnion during the August cruise.

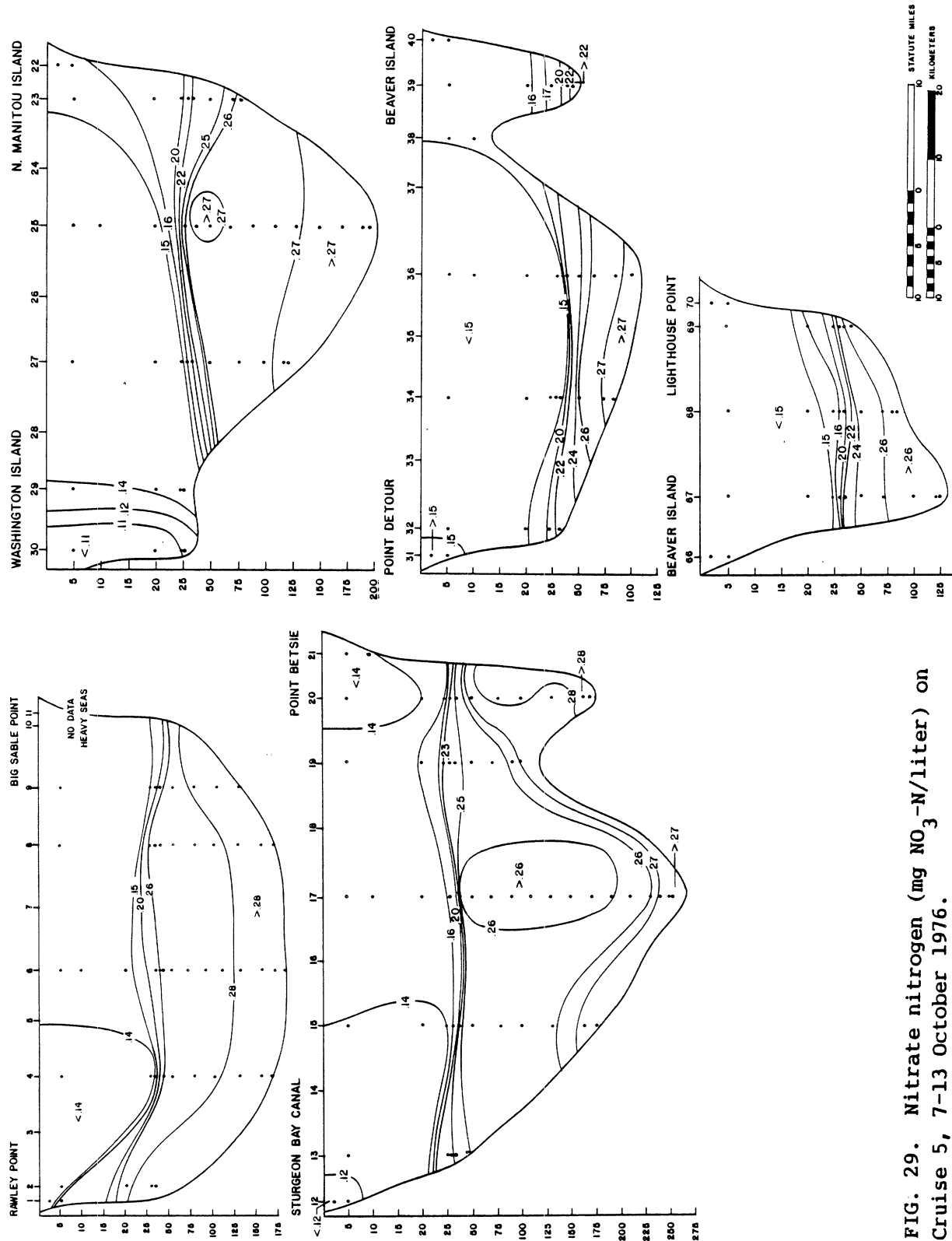


FIG. 29. Nitrate nitrogen (mg NO₃-N/liter) on Cruise 5, 7-13 October 1976.

Soluble Reactive Silica

In October there was more spatial structure for epilimnetic silica than was observed for temperature and nitrate. Smallest epilimnetic concentrations, <0.35 mg/liter, occurred at mid lake on the two northern transects, but on the two southern transects the lowest concentrations were found on the west ends of the transects (Fig. 30). Epilimnetic concentrations generally were <0.5 mg/liter. The largest epilimnetic concentrations, >0.7 mg/liter, were found at Station 30 probably reflecting water flowing out Death's Door. In the hypolimnion, concentrations ranged from 0.6 to 1.6 mg/liter with even larger concentrations in the bottom samples at some of the deep stations.

Particulate Silica

The spatial distribution of particulate silica in October was not strongly related to thermal structure. Probably one reason for the lack of structure was the low concentrations found on this cruise, as many of the values were <0.4 mg/liter. Values >0.4 mg/liter were found on the west ends of the three southernmost transects and in bottom and near-bottom samples from the deepest stations (Fig. 31). There was some indication that minimum values occurred at the top of the hypolimnion or the bottom of the metalimnion. This zone of minimum concentration, <0.2 or <0.3 mg/liter, was found at some stations on all transects.

Chlorophyll *a*

The influence of thermal stratification on the distribution of chlorophyll *a* in October was evident in that epilimnetic areas were readily distinguishable from hypolimnetic areas on the basis of concentration. Sharp

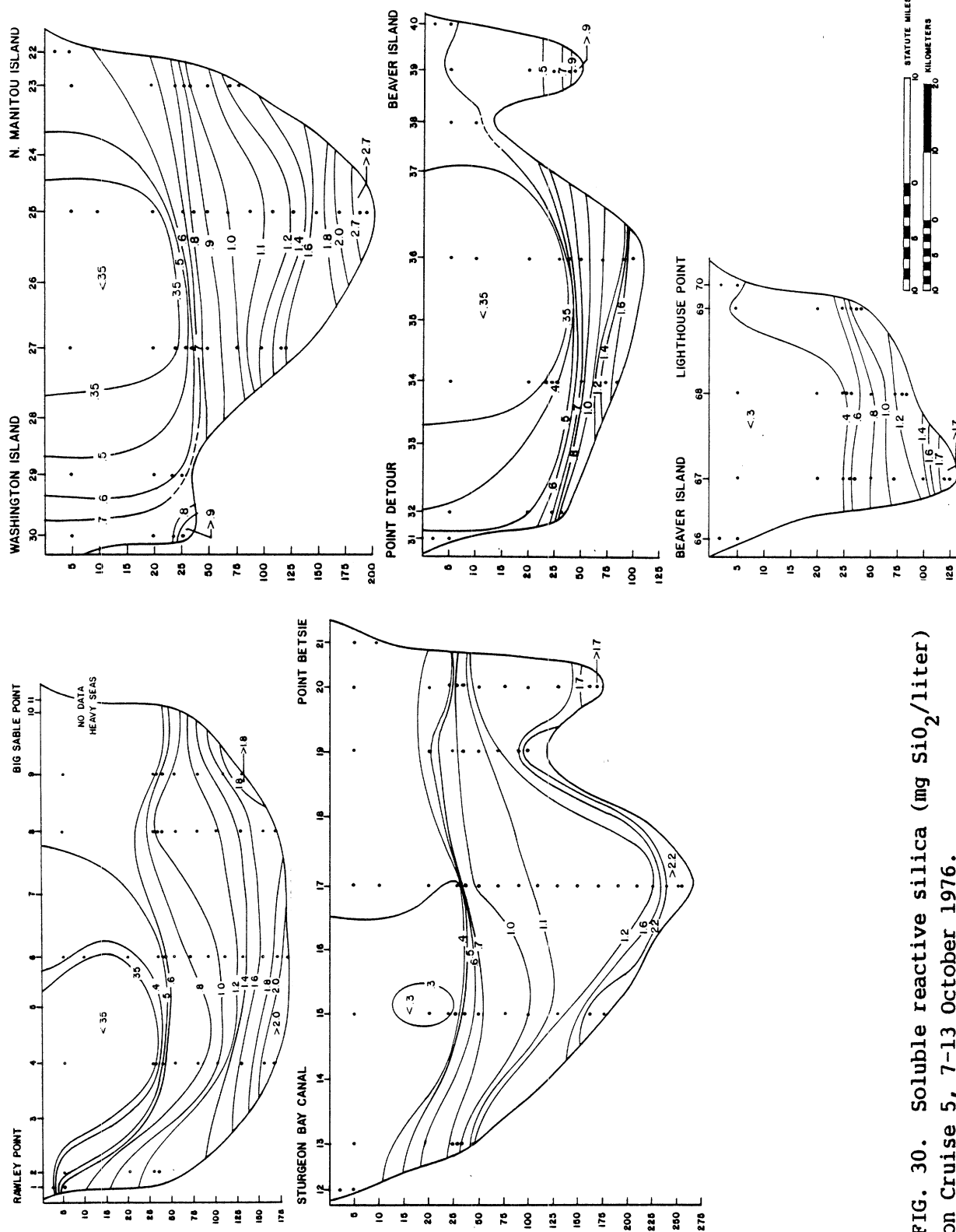


FIG. 30. Soluble reactive silica (mg SiO₂/liter) on Cruise 5, 7-13 October 1976.

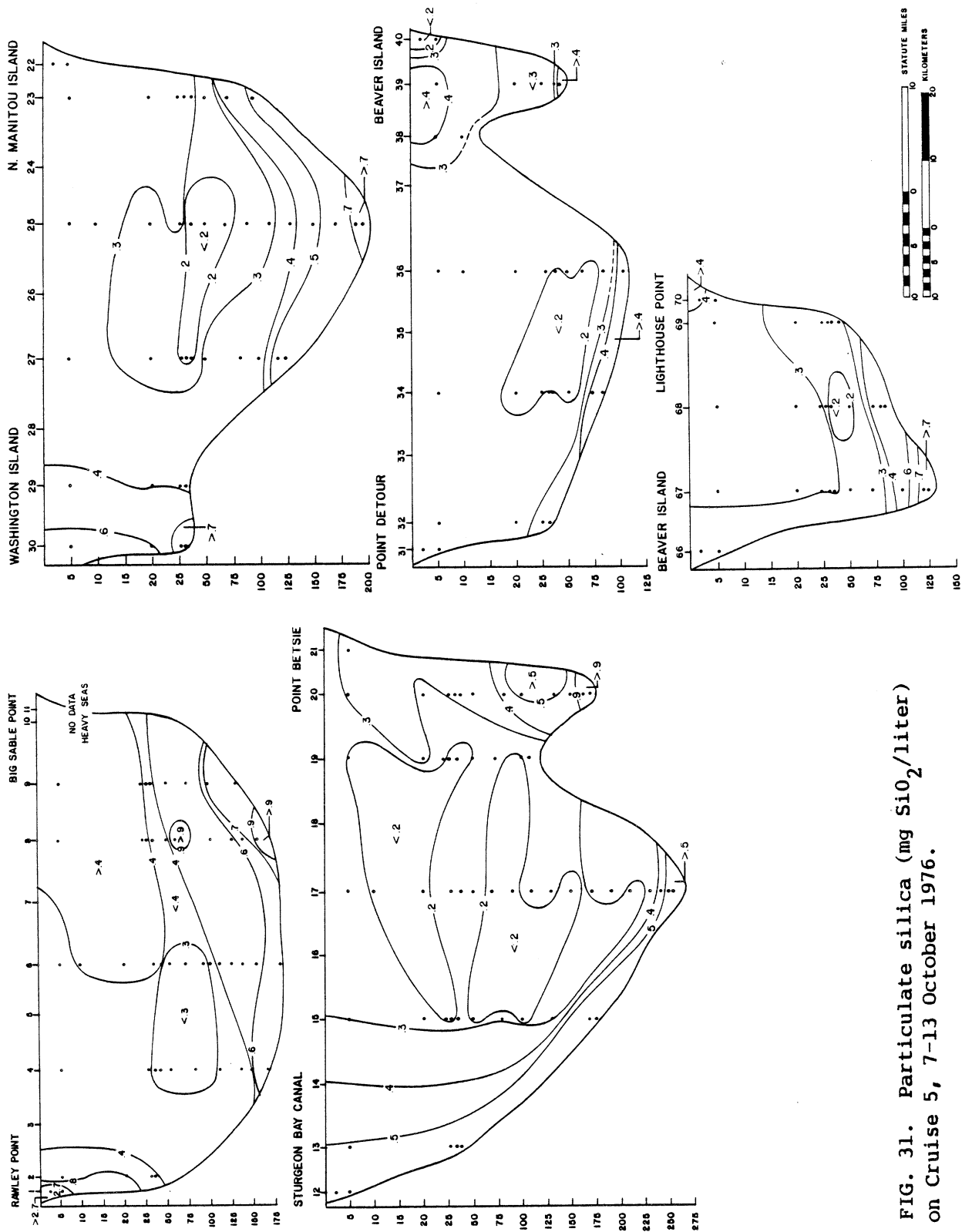


FIG. 31. Particulate silica (mg SiO₂/liter) on Cruise 5, 7-13 October 1976.

gradients in chlorophyll concentration were found in the metalimnion. Hypolimnetic concentrations were much lower than those in the epilimnion, being $<0.2 \mu\text{g/liter}$ over much of the volume on all transects. The zone with $<0.2 \mu\text{g/liter}$ extended from 50 m to the bottom on the three deep transects (Fig. 32).

Distributions in the epilimnion were relatively complex and the subsurface chlorophyll maximum that had been observed on the two earlier thermally stratified cruises was not present. Concentrations in the epilimnion were generally $>0.6 \mu\text{g/liter}$ and at nearshore stations concentrations were generally $>1 \mu\text{g/liter}$ (Fig. 32). Concentrations $>2 \mu\text{g/liter}$ were found at the west end of two transects, at Rawley Point and Death's Door.

Summary

The water column in October was thermally stratified as it had been in July and August. Temperatures were less variable than on previous cruises but had decreased to 12 to 14°C (Fig. 27). The epilimnetic depth generally ranged from 25 to 30 m. An atypical temperature structure was found at Station 30 which was attributed to water from Green Bay flowing out of Death's Door. Data for nitrate (Fig. 29), silica (Fig. 30), and chlorophyll (Fig. 32) also support the conclusion of transport from Green Bay through Death's Door. Epilimnetic values for pH generally ranged from 8.5 to 8.6. Values as low as 8.4 were present at a few stations (Fig. 28).

Spatial structures of nitrate and silica in October were more complex than thermal structure. Epilimnetic concentrations of nitrate ranged from 0.12 to 0.15 mg/liter, with the lowest values of 0.10 to 0.12 mg/liter at

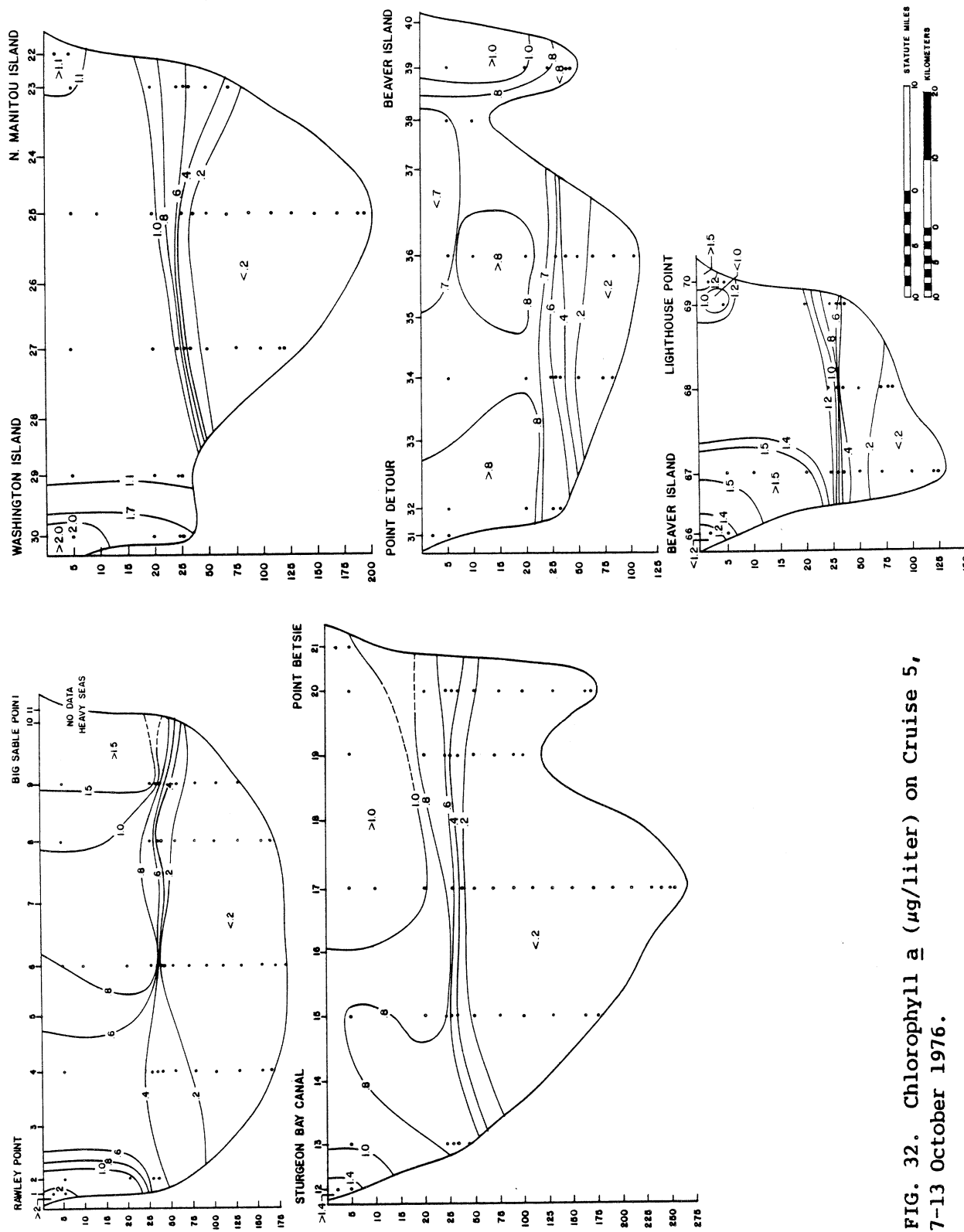


FIG. 32. Chlorophyll *a* ($\mu\text{g/liter}$) on Cruise 5, 7-13 October 1976.

Stations 12 and 30 near Death's Door and the entrance to the Sturgeon Bay Ship Canal (Fig. 29).

Epilimnetic silica concentrations at some stations on all transects were <0.35 mg/liter; however this pattern was not uniform over all transects (Fig. 30). Larger concentrations were found generally at stations closer to shore and not at midlake stations. The greatest surface concentration was 0.7 mg/liter at Station 30 which is undoubtedly a characteristic of Green Bay water flowing out of Death's Door.

Chlorophyll a structure in October was very complex. The largest epilimnetic concentrations tended to occur at nearshore stations or at stations close to shore. Maximum concentrations exceeded 2 μ g/liter at some stations (Fig. 32). The most consistent feature in the distribution of chlorophyll a was hypolimnetic concentrations <0.2 μ g/liter at all stations. The spatial distribution of particulate silica also was complex (Fig. 31) with no general pattern that could be attributed to thermal structure.

SEASONAL CHANGES

WATER TEMPERATURE

On the first two cruises in April and June, water temperatures at the master stations were isothermal with the exception of Station 36 in June. At Station 36 surface water temperature in June was 8°C indicating that thermal stratification was just beginning (Fig. 33). Water temperature at the four master stations in April was approximately 3°C which was the same as the average epilimnetic and hypolimnetic temperatures on this cruise (Table 2). By early June, temperatures at the master stations had increased to 4°C or greater. Because the master stations were among the deepest stations, surface temperatures, with the exception of shallow Station 36, were somewhat lower than the epilimnetic average of 6.7°C for the June cruise.

For the last three cruises in July, August, and October, the lake was thermally stratified. In July there was a large range in water temperatures at the master stations that resulted from the "cold core" of water found at Station 17. This "cold core" had a temperature of 12.5°C compared to epilimnetic temperatures of 17°C at Station 6 and 15°C at Stations 25 and 36 (Fig. 33), and an average epilimnetic temperature of 15.5°C (Table 2). The epilimnetic depth in July was shallow, about 10 m. From 10 to 30 m there was a rapid decrease in temperature and the hypolimnetic waters extended from 30 m to the bottom, except at Station 36 where the hypolimnion appeared to begin at 40 m.

The August cruise, like the July cruise, also occurred during the period of summer thermal stratification. In August the temperatures ranged from 18.5

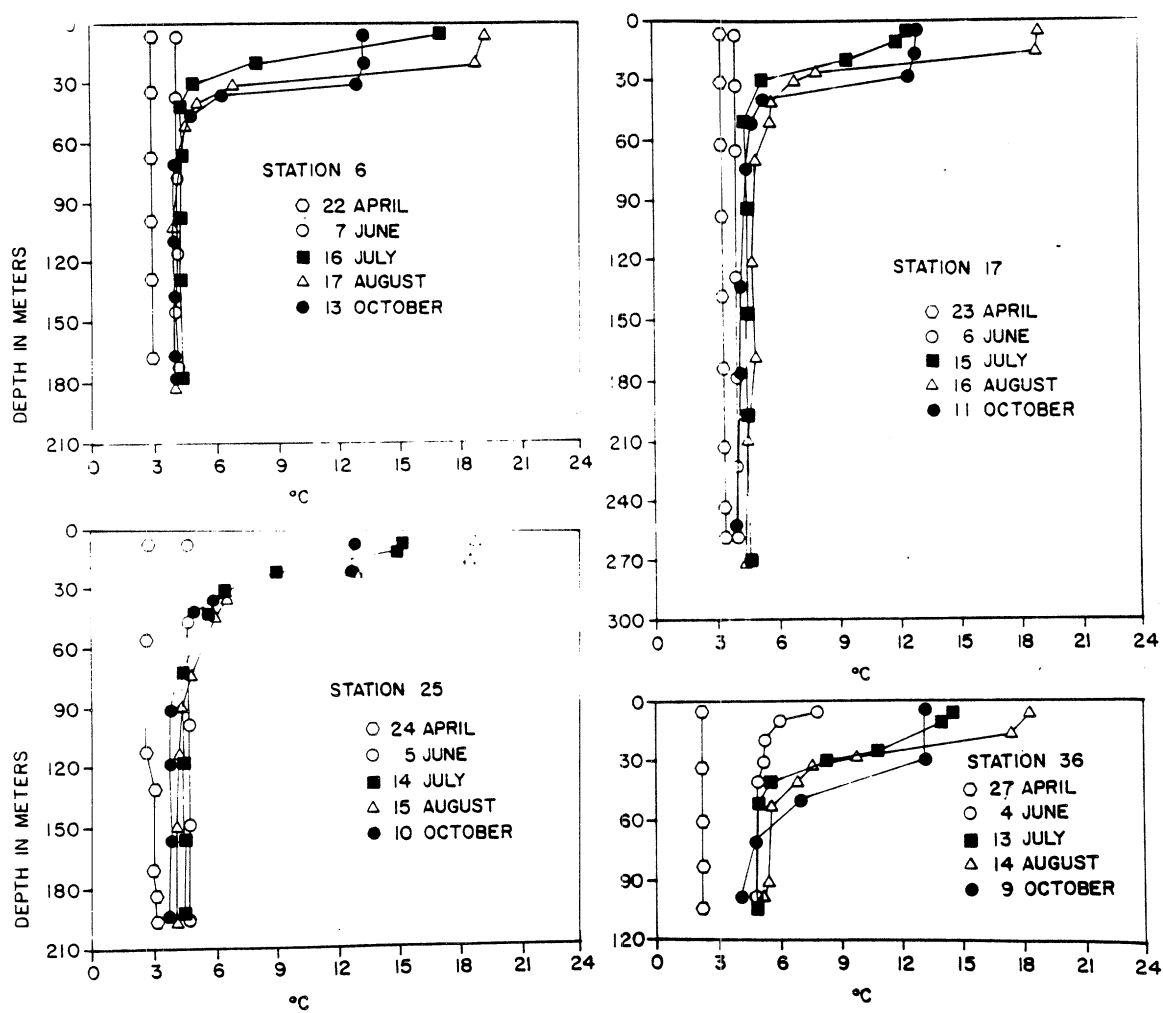


FIG. 33. Seasonal changes in water temperature at master stations.

TABLE 2. Seasonal changes in average water temperature ($^{\circ}\text{C}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation, N indicates number of samples for each stratum, NA indicates no data could be assigned to stratum. Epi, Meta, and Hypo refer to epilimnion, metalimnion, and hypolimnion.

| Stratum | Cruise | | | | |
|-----------|---------------|---------------|----------------|----------------|----------------|
| | April | June | July | August | November |
| Epi | 3.2 \pm 1.1 | 6.7 \pm 2.4 | 15.5 \pm 1.5 | 18.3 \pm 1.1 | 12.8 \pm 0.8 |
| N | (38) | (41) | (54) | (56) | (70) |
| Meta | (NA) | 7.2 \pm 0.4 | 8.9 \pm 1.9 | 9.5 \pm 2.7 | 8.1 \pm 1.4 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 3.1 \pm 0.6 | 4.5 \pm 0.5 | 4.8 \pm 0.5 | 4.9 \pm 0.5 | 4.5 \pm 0.6 |
| N | (86) | (95) | (106) | (96) | (92) |
| Nearshore | 5.5 \pm 1.8 | 9.6 \pm 2.3 | 15.2 \pm 2.8 | 16.6 \pm 3.6 | 12.7 \pm 0.6 |
| N | (18) | (22) | (22) | (23) | (20) |

to 19°C in the epilimnion at the master stations which was slightly warmer than the epilimnetic average of 18.3°C (Table 2). The epilimnion was deeper than in July, extending to 15 m at three of the stations and to 20 m at Station 6 (Fig. 33). The metalimnion was 10 to 15 m deep at the master stations, with the exception of Station 36 where it was 30 m deep and extended to approximately 45 m.

On the final cruise in October the epilimnion was much deeper than on the earlier thermally stratified cruises as a result of cooling in the surface waters and entrainment of deeper cooler waters. The epilimnetic depth had increased to 30 m at three of the stations but only to 20 m at Station 25 (Fig. 33) and water temperatures had decreased and were about equal to the

mean epilimnetic temperature of 12.8°C for this cruise (Table 2). The metalimnion at the three southernmost master stations extended to 30 m and was much deeper at Station 36 where it extended to a depth of at least 40 m.

Hypolimnetic temperatures, as would be expected, were uniform for the last four cruises. Hypolimnetic temperatures for these cruises also averaged less than 5°C (Table 2). Lower hypolimnetic temperatures were found in April when water column temperatures were less than the temperature of maximum density of water.

Nearshore temperatures during the study were significantly warmer than the average epilimnetic temperatures only on Cruise 1 in April and Cruise 2 in June (Table 2). During the rest of the year average nearshore temperatures were essentially the same as average epilimnetic temperatures in the offshore waters. In July and August the variability of nearshore temperatures was greater than the offshore epilimnetic temperatures and in August the nearshore average was actually less than the offshore average. The greater variability and lower average temperature for nearshore stations were probably caused by upwelled water at nearshore stations. Shallower nearshore waters also fluctuate more in temperature than offshore waters because these water masses with larger surface area-to-volume relationships respond more rapidly to changes in atmospheric and meteorological conditions than the deeper offshore waters.

HYDROGEN ION CONCENTRATION

At the master stations there was little variation in pH during the April and June cruises. On the April cruise pH measurements were obtained only on the southernmost transect at Station 6 and there was no vertical difference in

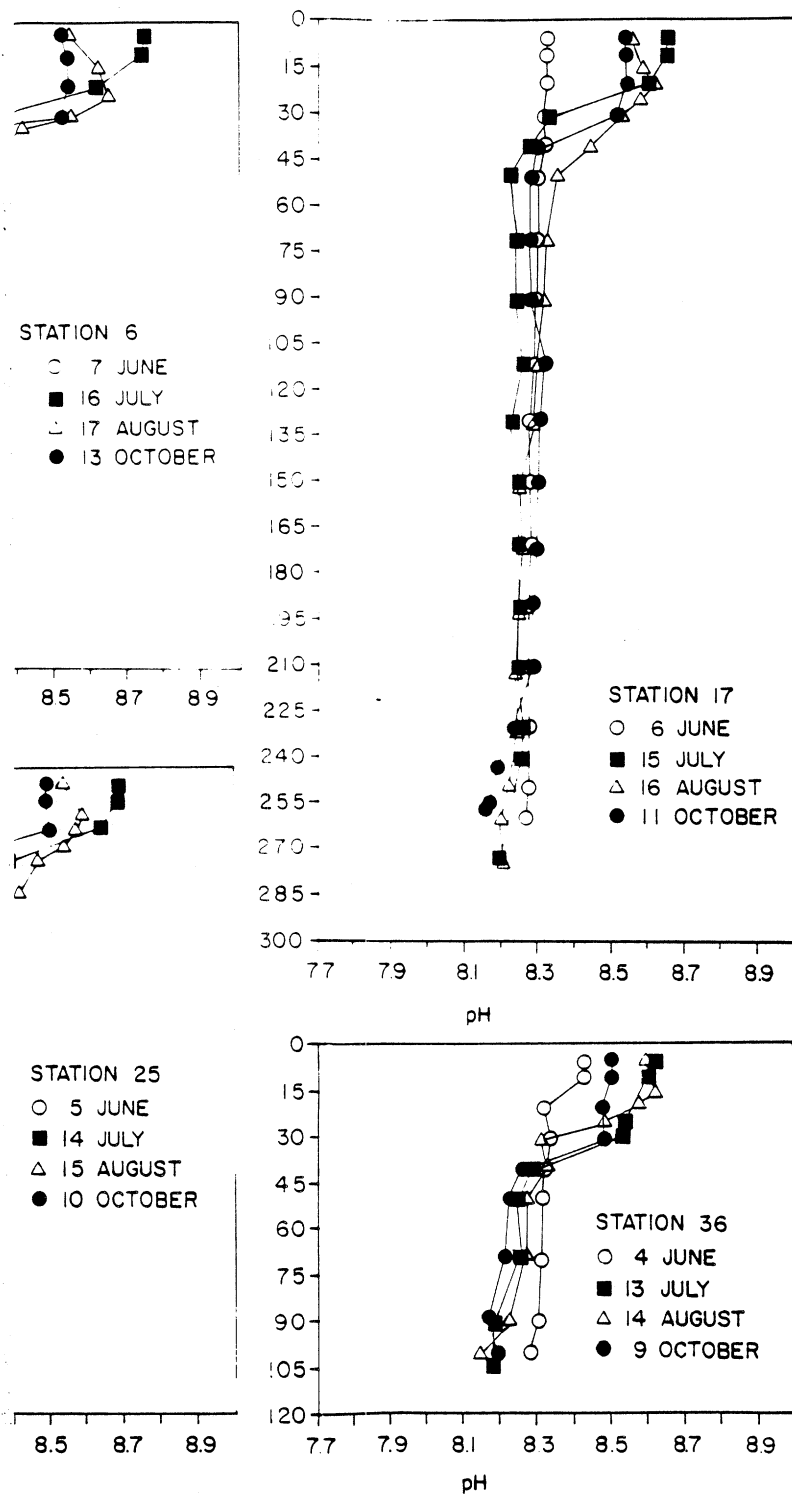
values which ranged generally from 8.3 to 8.35 (Fig. 34). Values for pH at the three deep stations on the June cruise were similar to those found at Station 6 in April. Values for pH in June were generally about 8.3, with a slight trend toward higher values at the top of the water column than at the bottom. This difference was small, being less than 0.1 of a pH unit. Effects of thermal stratification on the distribution of pH were evident at the shallow station, Station 36, where pH was 8.46 near the surface and decreased to 8.30 in the deepest waters.

After the onset of thermal stratification there was an obvious vertical structure of pH. Values in the epilimnetic and metalimnetic waters increased after stratification was established while those in the bottom waters appeared to decrease. In July, pH in the epilimnion ranged from 8.64 at Station 36 to 8.76 at Station 6 (Fig. 34). Hypolimnetic pH was <8.3 , with values as small as 8.15 being recorded in samples collected near the bottom.

The vertical structure of pH changed from July to August; epilimnetic values decreased and were in the range of 8.55 to 8.64 (Fig. 34). The most pronounced change in August was the presence of maximum pH values in the metalimnion. These values ranged from 8.60 to 8.65 at the three deepest stations.

On the October cruise epilimnetic pH values ranged from 8.50 to 8.54 and values in the hypolimnion ranged generally from 8.2 to 8.3 with values in some near-bottom samples being <8.2 (Fig. 34).

The pH values in the epilimnion and metalimnion at the master stations appeared to be different than those at the other stations sampled. On the last four cruises (June to October), epilimnetic pH values (Fig. 34) were greater than epilimnetic means for offshore stations (Table 3). The August



anges in pH at master stations.

metalimnetic maxima for the master stations were also greater than the August mean for metalimnetic samples. These differences were about 0.2 pH units, indicating that the detailed vertical sampling at the master stations may have revealed structure that was missed with less intensive sampling at other offshore stations.

NITRATE NITROGEN

On the first two cruises in April and June the distribution of nitrate at the four master stations was generally homogeneous. There was no decrease in concentrations between the two cruises (Fig. 35) as might be suggested from the small difference in epilimnetic averages for the April and June cruises (Table 4). On both cruises concentrations at the two deepest stations, Stations 17 and 25, ranged from 0.24 to 0.25 mg/liter. At the other deep station, Station 6, concentrations actually appeared to be larger on the June cruise than on the April cruise. At the shallow station, Station 36, nitrate concentrations were smaller on both cruises than those at the deeper stations and also decreased from April to June. In April, concentrations at Station 36 ranged from 0.21 to 0.22 mg/liter over most of the water column. Concentrations were slightly greater near the bottom and by June had decreased to <0.21 mg/liter over most of the water column with concentrations as low as 0.20 mg/liter occurring at 5 m. The lower concentrations at 5 and 10 m are the result of thermal stratification and subsequent nitrate utilization by epilimnetic phytoplankton communities.

The vertical distribution of nitrate at the master stations was strongly related to the thermal structure. During thermal stratification average epilimnetic concentrations of nitrate at all stations decreased relative to

TABLE 3. Seasonal changes in average hydrogen ion concentration (pH) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | April | June | July | August | November |
| Epi | 8.35 \pm 0.10 | 8.43 \pm 0.11 | 8.58 \pm 0.14 | 8.57 \pm 0.06 | 8.49 \pm 0.05 |
| N | (12) | (60) | (82) | (80) | (90) |
| Meta | (NA) | 8.47 \pm 0.02 | 8.49 \pm 0.13 | 8.47 \pm 0.09 | 8.28 \pm 0.05 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 8.30 \pm 0.05 | 8.32 \pm 0.06 | 8.23 \pm 0.11 | 8.26 \pm 0.07 | 8.25 \pm 0.06 |
| N | (26) | (97) | (124) | (101) | (108) |
| Nearshore | 8.55 \pm 0.05 | 8.49 \pm 0.07 | 8.44 \pm 0.21 | 8.50 \pm 0.20 | 8.48 \pm 0.04 |
| N | (4) | (22) | (22) | (23) | (20) |

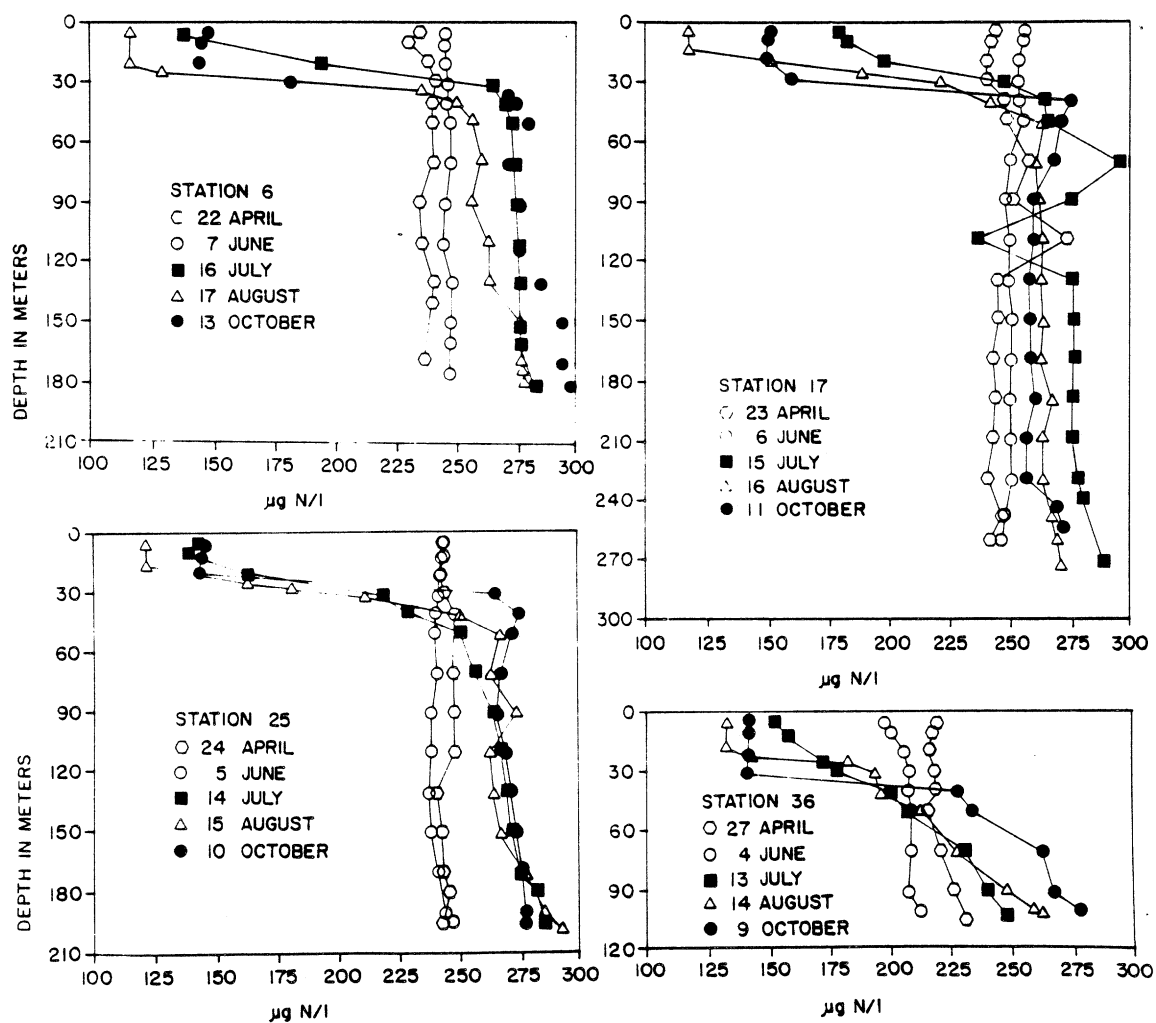


FIG. 35. Seasonal changes in nitrate nitrogen at master stations.

TABLE 4. Seasonal changes in average nitrate-nitrogen ($\mu\text{g N/liter}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|--------------|--------------|--------------|--------------|--------------|
| | April | June | July | August | October |
| Epi | 237 \pm 27 | 221 \pm 32 | 155 \pm 25 | 126 \pm 18 | 151 \pm 17 |
| N | (54) | (79) | (82) | (80) | (90) |
| Meta | (NA) | 173 \pm 12 | 189 \pm 27 | 186 \pm 36 | 240 \pm 31 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 241 \pm 20 | 233 \pm 22 | 254 \pm 30 | 257 \pm 24 | 266 \pm 24 |
| N | (114) | (99) | (123) | (101) | (108) |
| Nearshore | 202 \pm 63 | 155 \pm 50 | 153 \pm 29 | 145 \pm 40 | 136 \pm 22 |
| N | (18) | (22) | (22) | (23) | (20) |

concentrations present during the thermally mixed period in April and June. The largest decrease occurred from June to July when epilimnetic averages decreased from 0.22 mg/liter to 0.16 mg/liter (Table 4). The average concentration decreased to 0.13 mg/liter in August but then increased to 0.15 mg/liter in October when epilimnetic cooling and entrainment of nitrogen-rich deeper waters increased the concentration of nitrogen in the epilimnion.

Average hypolimnetic concentrations decreased from 0.24 to 0.23 mg/liter during the two thermally mixed cruises in April and June (Table 4). After stratification hypolimnetic concentrations were greater than those earlier in the year (Fig. 35) and appeared to increase slightly during the season (Table 4). A general increase probably would be expected as the result of

regeneration of nitrogenous materials in the hypolimnion and possibly to the nitrification of ammonia.

Metalimnetic concentrations were no different on the two thermally stratified cruises in July and August (Table 4). Concentrations averaged about 0.19 mg/liter, significantly less than the average of 0.24 mg/liter which was found during the October cruise. The sharp increase in metalimnetic concentrations from August to October reflects entrainment of nitrate-rich waters as the epilimnion deepened during the fall. The smallest metalimnetic concentrations were found in June when only shallow stations were stratified. The resulting average obtained from three samples (Table 4) therefore has little meaning in terms of lake-wide conditions.

Epilimnetic concentrations at the four master stations during the thermally stratified cruises were generally those that would be expected from the epilimnetic averages obtained at all stations. The major exception is that the "cold core" water at Station 17 during July had a nitrate concentration ranging from 0.18 to 0.19 mg/liter (Fig. 35) which was more characteristic of metalimnetic water than epilimnetic water (Table 4). At the other two deep master stations, concentrations in July ranged from 0.13 to 0.14 mg/liter and were at the low end of the range expected from epilimnetic averages for all stations. Values at Station 36 were 0.15 to 0.16 mg/liter which were consistent with the epilimnetic average of 0.155 mg/liter. In August, epilimnetic nitrate concentrations at the master stations ranged from 0.11 to 0.12 mg/liter at the three deep stations, with slightly larger concentrations being found at Station 25 (Fig. 35). These concentrations were lower than the average epilimnetic concentration of 0.13 mg/liter for this cruise (Table 4). On the other hand, concentrations at Station 36 averaged

0.14 mg/liter which was essentially equal to the average concentration. On the October cruise epilimnetic concentrations at the three master stations, with the exception of Station 17, ranged from 0.14 to 0.15 mg/liter, less than the average concentration of 0.15 mg/liter. For the epilimnion, the range for Station 17 of 0.15 to 0.16 mg/liter was greater than the cruise average for all stations.

Seasonal changes in nitrate at Station 36, the shallowest of these four stations, differed from the patterns found at the three deeper stations. During the first two cruises the epilimnetic concentrations at Station 36 (Fig. 35) were considerably less than the epilimnetic averages for the study area (Table 4), but on the three thermally stratified cruises concentrations at Station 36 were within one standard deviation of the mean concentration for the epilimnion. This effect could be attributed to one of two factors, either to an input of nitrogen-rich water from the Straits of Mackinac area or to the fact that more nitrogen may have been entrained from deep waters at this station than at the other stations on the transect.

Hypolimnetic data suggest an increase in nitrate concentration from the second cruise in June until the final cruise in October. The concentration differences, particularly during the three stratified cruises, are relatively small, but there is an increasing trend in average concentrations (Table 4). Inspection of the data for the three deep master stations suggests that this increase may have occurred throughout the hypolimnion rather than in the waters near the bottom (Fig. 35). Profiles for October at these stations show larger concentrations in the metalimnion than in deeper layers near the top of the hypolimnion. If this increase is real, it must be attributed to the regeneration of nitrogen from the decomposition of organisms and possibly from

the nitrogenous waste products of plankton and nekton. Concentrations in bottom samples also appeared to increase at all the master stations; however, this increase is relatively small and is restricted to depths very close to the bottom.

Hypolimnetic nitrate distribution at Station 36 was different than that at the three deeper stations (Fig. 35). Concentrations generally were less at Station 36 on all cruises than at the deeper stations. In addition, the distribution generally indicated a fairly steady increase in concentration from the top of the hypolimnion to the bottom of the hypolimnion; whereas at deeper stations, hypolimnetic concentrations were more uniform over the hypolimnetic depth.

SOLUBLE REACTIVE SILICA

During the homothermal period that was sampled on the April and June cruises, silica concentrations at the four master stations were generally homogeneous over the water column. Concentrations at shallow Station 36 were much less than those at the deeper stations and decreased markedly from April to June. In April, concentrations at Station 36 ranged from 0.7 to 0.8 mg/liter in comparison to concentrations at the deeper stations that were 1 mg/liter, ranging to as large as 1.2 mg/liter (Fig. 36). By June, cruise concentrations at Station 36 had decreased to 0.4 to 0.5 mg/liter. Decreases from April to June, although smaller than at Station 36, were also observed at Stations 17 and 25 but not at Station 6. Concentrations for April and June at the deep master stations were larger than the epilimnetic averages for these two cruises (Table 5), a result which would be expected because the master stations are among the deepest stations sampled during the study.

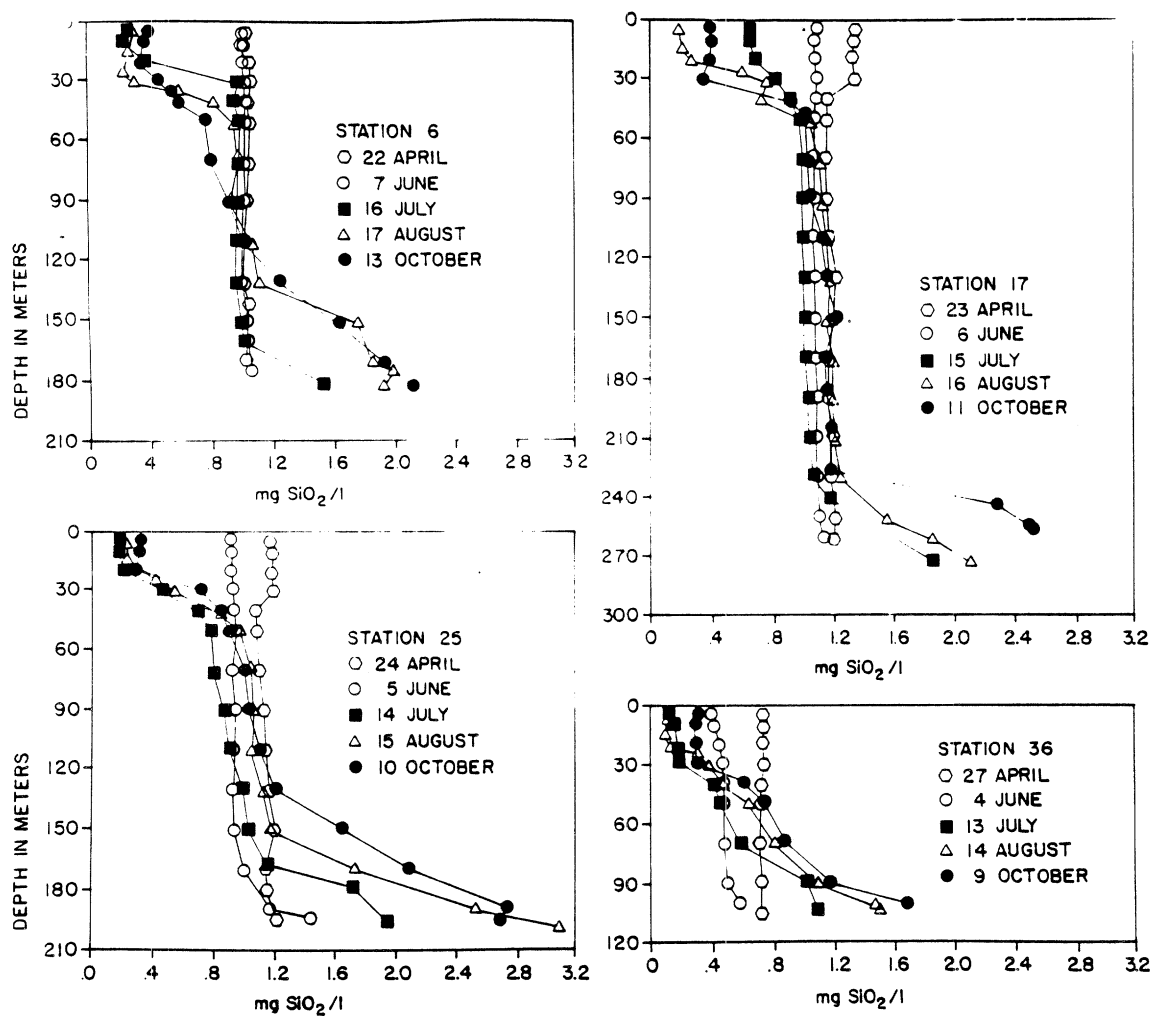


FIG. 36. Seasonal changes in soluble reactive silica at master stations.

TABLE 5. Seasonal changes in average soluble reactive silica (mg SiO₂/liter) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | |
|-----------|-----------------|-----------------|-----------------|-----------------|
| | April | June | July | August |
| Epi | 0.96 \pm 0.25 | 0.74 \pm 0.32 | 0.25 \pm 0.22 | 0.19 \pm 0.09 |
| N | (54) | (79) | (82) | (80) |
| Meta | (NA) | 0.33 \pm 0.10 | 0.38 \pm 0.24 | 0.43 \pm 0.26 |
| N | (NA) | (3) | (41) | (65) |
| Hypo | 1.06 \pm 0.21 | 0.85 \pm 0.30 | 0.99 \pm 0.41 | 1.25 \pm 0.48 |
| N | (114) | (99) | (123) | (101) |
| Nearshore | 0.48 \pm 0.37 | 0.31 \pm 0.31 | 0.30 \pm 0.26 | 0.44 \pm 0.45 |
| N | (18) | (22) | (22) | (23) |

On the June cruise the silica profiles at Stations 25 and 36 differed from the homogeneous pattern found at Stations 6 and 17. At Station 25 there was an obvious increase in concentration for samples collected near the bottom, which was also true to a lesser extent at Station 36. In addition, at Station 36 the influence of thermal stratification was seen in that surface silica concentrations were slightly depleted relative to those at deeper depths.

Epilimnetic silica concentrations decreased after the June cruise and establishment of thermal stratification in July and August (Table 5). Epilimnetic concentrations at the four master stations during July and August (Fig. 36) were within the range that would be expected from the epilimnetic cruise averages with the exception that the "cold core" at Station 17 in July had silica concentrations that ranged from 0.65 to 0.75 mg/liter, about 0.4 mg/liter greater than the epilimnetic average. Minimum epilimnetic concentrations, averaging 0.2 mg/liter (Table 5), were found in August. By October, concentrations at the three deep stations had increased to 0.7 to 0.8 mg/liter as the result of entrainment of deep silica-rich water. These concentrations were larger than the epilimnetic average of 0.45 mg/liter for all stations and, in fact, were nearly equal to the metalimnetic average for October.

Shapes of silica profiles at the master stations compared with those for nitrate show generally that silica in the metalimnion and the upper part of the hypolimnion (Fig. 36) was relatively more depleted than nitrogen (Fig. 35), but that in the bottom waters silica was enriched to a much greater extent than nitrogen. These data indicate that the near-bottom area and

possibly the sediments are much more important in silica recycling than would be the case for nitrogen.

PARTICULATE SILICA

During the thermally mixed period in the spring a certain amount of structure developed in the vertical distribution of particulate silica. In April, at the three deep stations, concentrations varied little from the surface to the bottom. At Stations 6 and 25 concentrations ranged from 0.2 to 0.3 mg/liter and were slightly less at the deepest station, Station 17, where concentrations were generally 0.2 mg/liter or less (Fig. 37). At shallow Station 36 concentrations ranged from 0.4 to 0.5 mg/liter which was more representative of average epilimnetic and hypolimnetic concentrations in April (Table 6) than the smaller than average concentrations at the deeper stations. On the second cruise in June there was some evidence of vertical structure at Station 17 but the structure was much more evident at Stations 6, 25, and 36. At Station 25 concentrations of particulate silica below 110 m were 0.5 mg/liter, much greater than the concentrations above that depth. At Station 6, the maximum concentration, 0.5 mg/liter, was observed at 20 m. A subsurface maximum was also found at this station on the three following cruises.

During the thermally stratified cruises in July and August, the general pattern of vertical distribution at the master stations was a relatively large concentration in the epilimnion or metalimnion, below which was a zone of minimum concentration and a zone of maximum concentration near the bottom. This pattern is particularly evident for Station 25 in July and at Station 6 in July, August, and October (Fig. 37). Data for all stations showed that

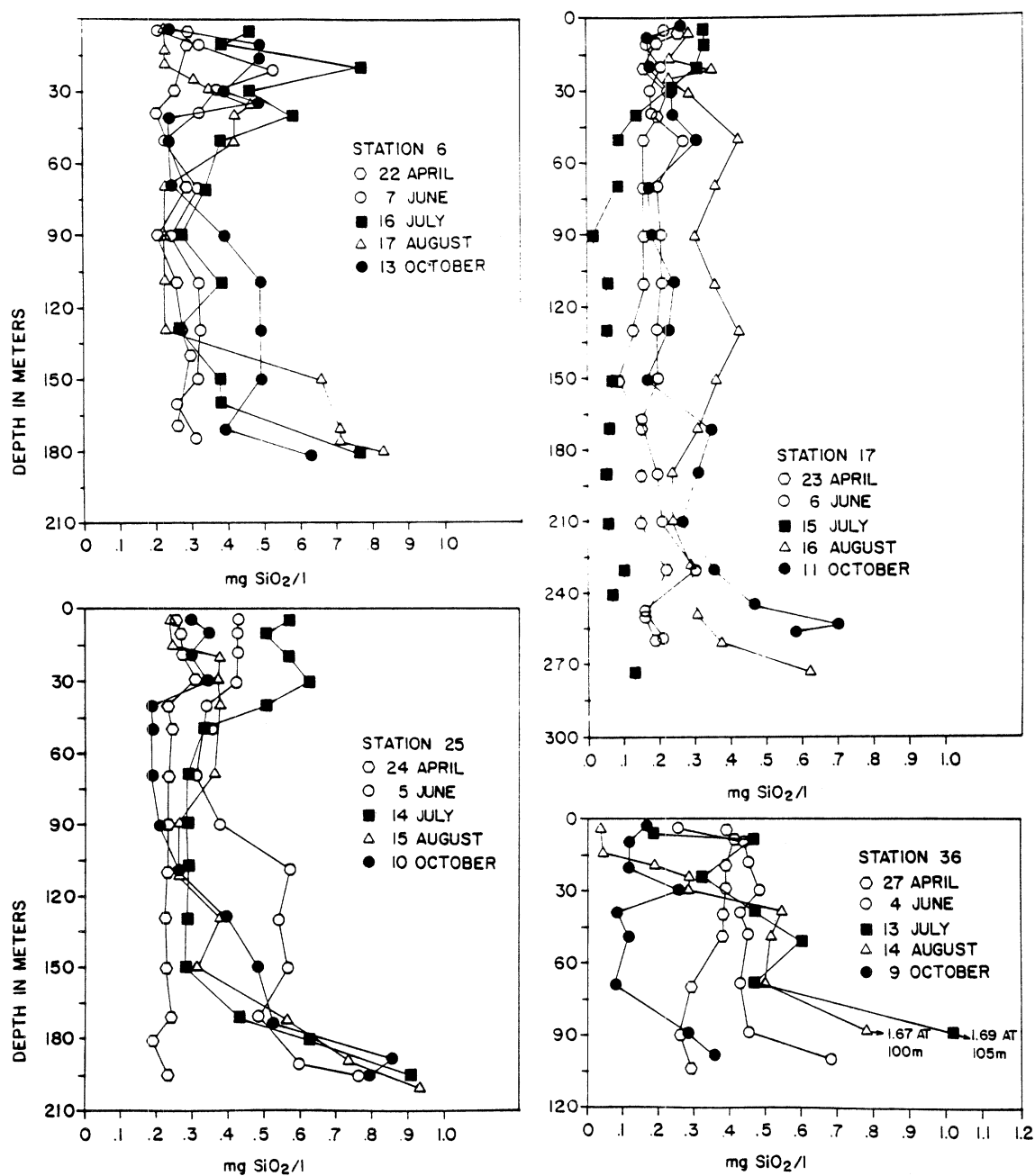


FIG. 37. Seasonal changes in particulate silica at master stations.

TABLE 6. Seasonal changes in average particulate silica (mg SiO₂/liter) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|------------|-----------|-----------|-----------|------------|
| | April | June | July | August | October |
| Epi | .43 + .24 | .40 + .14 | .49 + .18 | .36 + .14 | .33 + .13 |
| N | (54) | (79) | (78) | (79) | (90) |
| Meta | (NA) | .61 + .06 | .65 + .20 | .50 + .17 | .33 + .10 |
| N | (NA) | (3) | (39) | (64) | (27) |
| Hypo | .38 + .19 | .45 + .19 | .72 + .41 | .63 + .37 | .56 + 1.21 |
| N | (111) | (99) | (108) | (100) | (108) |
| Nearshore | 1.03 + .88 | .50 + .23 | .73 + .29 | .56 + .23 | .60 + .79 |
| N | (18) | (22) | (22) | (23) | (18) |

average concentrations in the metalimnion for July and August were greater than those in the epilimnion (Table 6).

Mean concentrations of particulate silica in different thermal zones of the lake illustrate several patterns that are related to dynamics of silica. Means for the first two cruises indicate uniform distributions from surface to the bottom with very little change, if any, in average concentration from April to June (Table 6). Maximum epilimnetic concentrations were found in July. During July and August, concentrations were greater in the metalimnion than in the epilimnetic waters. These large concentrations reflect the subsurface chlorophyll maximum also found in this zone. The data also indicate that the subsurface maximum was present in June, although the larger average metalimnetic concentration was based on only three samples.

In the hypolimnion, concentrations increased in July after thermal stratification was established, and then progressively decreased until the last sampling in October (Fig. 37). Hypolimnetic averages for data from all stations (Table 6) are biased by the near-bottom samples that generally have greater concentrations than the average (Fig. 37). These larger than average concentrations contribute to the relatively large variances obtained for the hypolimnetic averages on the stratified cruises in July, August, and October.

CHLOROPHYLL a

In April, on the first cruise during homothermal conditions, there was no obvious vertical structure at any of the master stations. Chlorophyll concentrations at shallow Station 36 ranged from 2.4 to 2.7 $\mu\text{g/liter}$ which was much larger than the concentrations at the three deeper stations (Fig. 38).

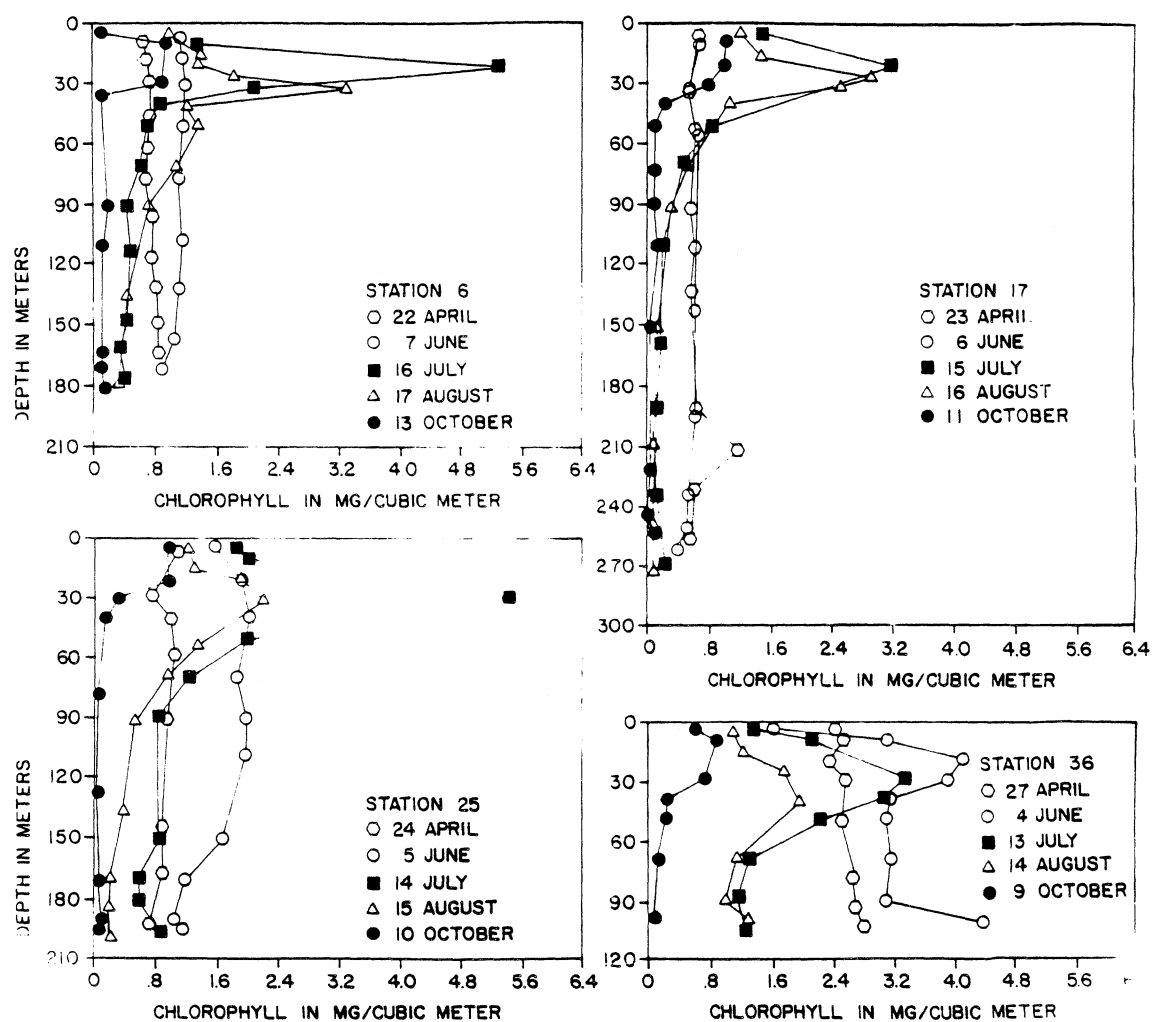


FIG. 38. Seasonal changes in chlorophyll *a* at master stations.

At the three deeper stations concentrations were generally $<1.1 \mu\text{g/liter}$ and at Station 17, the deepest station, were generally $<0.7 \mu\text{g/liter}$.

On the June cruise, chlorophyll concentrations at the four master stations, with the exception of Station 17, were greater than in April. The greatest increase occurred at Station 36 where a subsurface maximum of $4.2 \mu\text{g/liter}$ was found in the metalimnion at 25 m (Fig. 38); Station 36 was the only master station that was thermally stratified in June. At Station 25 chlorophyll concentrations had increased to a maximum of $2 \mu\text{g/liter}$ with some evidence for the beginning of vertical structure.

Vertical structure in chlorophyll concentrations was very evident on the three cruises conducted while the lake was thermally stratified. During the July and August cruises the metalimnetic chlorophyll maximum was well developed and was found at all four master stations (Fig. 38). In October the vertical structure changed in that maximum chlorophyll concentrations were found in the epilimnion and minimum concentrations were present in the lower metalimnion and hypolimnion. The hypolimnetic mean for the October cruise was $0.25 \mu\text{g/liter}$ compared to an epilimnetic mean of $0.90 \mu\text{g/liter}$ (Table 7). Hypolimnetic concentrations at the three deep master stations were much less than the cruise mean and were generally $<0.1 \mu\text{g/liter}$ (Fig. 38).

The metalimnetic chlorophyll maximum that was present in July and August was found at depths ranging from 20 to 30 m at the three deep stations (Fig. 38). In July the maximum was found at 20 m at Stations 6 and 17 and at deeper depths in August (25 to 30 m). Concentrations were as large as $5.5 \mu\text{g/liter}$ in July and were greater than August concentrations that did not exceed $3.2 \mu\text{g/liter}$. At shallow Station 36 the maximum concentration in the subsurface layer occurred in June when the water column was thermally

TABLE 7. Seasonal changes in average chlorophyll a ($\mu\text{g/liter}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | April | June | July | August | October |
| Epi | 2.22 \pm 2.15 | 2.08 \pm 1.04 | 1.69 \pm 0.50 | 1.62 \pm 0.51 | 0.90 \pm 0.31 |
| N | (53) | (79) | (82) | (80) | (84) |
| Meta | (NA) | 4.26 \pm 0.43 | 3.90 \pm 1.39 | 2.30 \pm 0.72 | 0.48 \pm 0.21 |
| N | (NA) | (3) | (41) | (65) | (26) |
| Hypo | 1.55 \pm 1.18 | 2.12 \pm 1.34 | 1.43 \pm 1.25 | 0.90 \pm 0.65 | 0.25 \pm 0.26 |
| N | (114) | (99) | (124) | (101) | (102) |
| Nearshore | 7.23 \pm 5.64 | 3.44 \pm 2.47 | 1.90 \pm 0.44 | 1.83 \pm 0.59 | 1.43 \pm 0.40 |
| N | (18) | (22) | (22) | (23) | (16) |

stratified. This concentration was 4.2 $\mu\text{g/liter}$. In July the concentration was 3.4 $\mu\text{g/liter}$ and decreased to only 2 $\mu\text{g/liter}$ in August. Average metalimnetic concentrations of chlorophyll a were also greater during July and August average cruise concentrations in either the epilimnion or hypolimnion (Table 7).

TOTAL PHOSPHORUS

On the first two cruises during homothermal conditions there was little indication of vertical structure in total phosphorus concentrations at any master station (Fig. 39). Peaks in concentration occurred only at one or two depths in any profile. Data for the master stations and cruise means (Table 8) indicate that total phosphorus concentrations decreased from the April cruise to the June cruise. However, large variances associated with these measurements indicate that the differences are not statistically significant.

During the thermally stratified cruises total phosphorus concentrations increased in near-bottom samples compared to values in April and June (Fig. 39). Obviously some of this increase resulted from observed increases in soluble reactive phosphorus concentrations for near-bottom samples. Even though there was an increase in total phosphorus concentrations in near-bottom samples, cruise means for the hypolimnetic samples were no greater than the epilimnetic averages (Table 8). In fact, on the October cruise the hypolimnetic mean was about 1 $\mu\text{g/liter}$ less than the epilimnetic average. In June and August, largest average concentrations were found in the metalimnetic strata. Large variations are associated with these averages so,

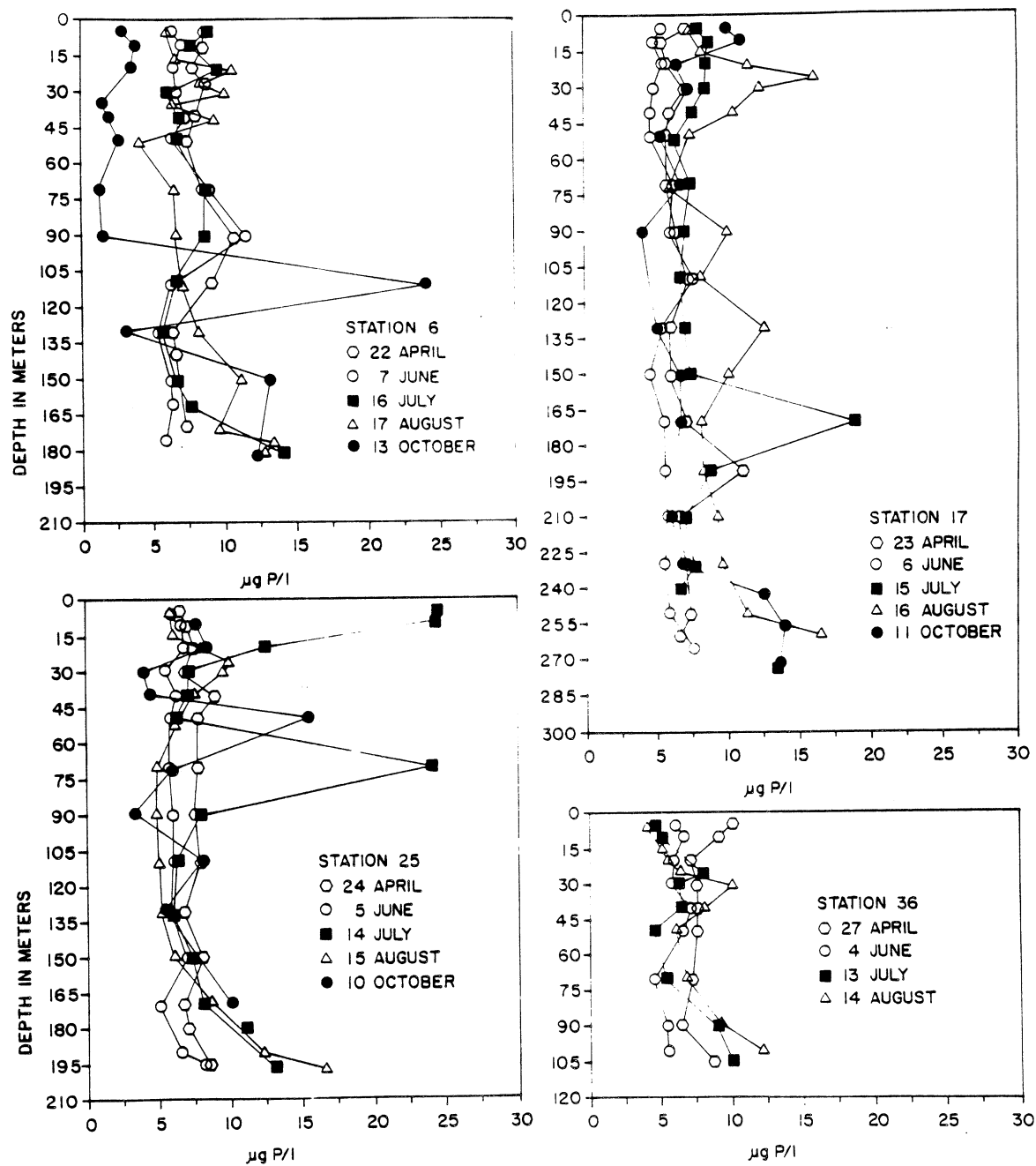


FIG. 39. Seasonal changes in total phosphorus at master stations.

TABLE 8. Seasonal changes in average total phosphorus ($\mu\text{g/liter}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|----------------|---------------|----------------|---------------|---------------|
| | April | June | July | August | October |
| Epi | 7.8 \pm 2.0 | 6.8 \pm 1.3 | 8.9 \pm 4.1 | 8.0 \pm 2.5 | 8.0 \pm 3.6 |
| N | (54) | (78) | (82) | (80) | (90) |
| Meta | (NA) | 7.1 \pm 1.1 | 9.2 \pm 3.8 | 9.1 \pm 2.5 | 7.3 \pm 1.5 |
| N | (NA) | (3) | (40) | (65) | (27) |
| Hypo | 7.5 \pm 1.3 | 6.6 \pm 1.4 | 8.8 \pm 3.9 | 8.9 \pm 3.1 | 6.9 \pm 2.2 |
| N | (113) | (99) | (124) | (101) | (108) |
| Nearshore | 10.6 \pm 5.1 | 7.9 \pm 2.6 | 10.5 \pm 5.9 | 9.8 \pm 2.5 | 8.0 \pm 3.3 |
| N | (18) | (22) | (22) | (23) | (20) |

even though the trends may indicate larger averages, the differences between means are not statistically significant (t-tests, $\alpha = 0.05$).

Vertical structure in total phosphorus concentrations is suggested by data from the master stations for the three thermally stratified cruises that were conducted during July, August, and October. In July, concentrations in the epilimnion were larger than in metalimnetic waters of the three deep stations, particularly at Station 25 where total phosphorus concentrations were 24 $\mu\text{g/liter}$ in the epilimnion (Fig. 39). These large values for July obviously are not representative values and may be the result of sample contamination or possibly to sampling artifacts or bias. In August, concentrations were greater in the metalimnion and lower part of the

epilimnion than in the waters above or below. In October, minimum values tended to occur at the lower part of the metalimnion or the top of the hypolimnion, except at Station 17.

TOTAL SOLUBLE PHOSPHORUS

Total soluble phosphorus (Table 9) represented a large fraction of the total phosphorus concentrations (Table 8). For hypolimnetic samples, the soluble component was at least 50% of the total and ranged to as much as 60% of the average total phosphorus concentration. Averages of the soluble fraction of epilimnetic samples were also a large proportion of the total phosphorus concentration, but were less than 50% during July and August. Average total soluble phosphorus concentrations in the metalimnion were a relatively smaller proportion of the total in July and August, indicating that the largest concentrations of particulate phosphorus occurred in the metalimnion during these 2 months.

A large fraction of the total soluble phosphorus concentration was refractory because soluble reactive phosphorus concentrations (not presented in this report) rarely exceeded 2 $\mu\text{g P/L}$ (Bartone and Schelske 1982), except for near-bottom samples.

AMMONIA NITROGEN

Large variations in ammonia concentrations were found for all strata sampled (Table 10). Values for specific depths can vary greatly from the mean when samples are contaminated and some of the observed variability undoubtedly resulted from contamination. However, the small concentrations reported for most samples indicate that significant contamination occurred infrequently.

TABLE 9. Seasonal changes in average total soluble phosphorus ($\mu\text{g P/liter}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|---------------|---------------|---------------|---------------|---------------|
| | April | June | July | August | October |
| Epi | 4.7 \pm 3.5 | 3.4 \pm 0.6 | 4.2 \pm 3.4 | 3.6 \pm 1.2 | 4.7 \pm 2.8 |
| N | (54) | (79) | (82) | (80) | (99) |
| Meta | (NA) | 3.5 \pm 0.6 | 3.5 \pm 1.9 | 3.9 \pm 1.5 | 4.2 \pm 1.1 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 4.3 \pm 1.2 | 3.3 \pm 0.6 | 5.1 \pm 3.8 | 5.0 \pm 2.0 | 3.9 \pm 1.2 |
| N | (114) | (99) | (123) | (101) | (108) |
| Nearshore | 4.7 \pm 2.2 | 3.3 \pm 0.9 | 4.3 \pm 3.7 | 3.8 \pm 1.2 | 4.7 \pm 1.4 |
| N | (18) | (22) | (22) | (23) | (20) |

On the two cruises conducted during isothermal conditions, it is difficult to discern any pattern in vertical structure in ammonia concentrations. There is some indication that concentrations were lower in surface waters than near the bottom. This trend can be seen by comparing cruise means for epilimnetic and hypolimnetic samples (Table 10). On the June cruise, near-surface samples at the three deep master stations tended to increase in concentration to a depth of about 60 m (Fig. 40). Below 60 m at Stations 6 and 17, there was a zone of minimum values which extended to about 150 m. The pattern of mid-depth minimum values, however, was not found at Station 25.

TABLE 10. Seasonal changes in average ammonia concentrations ($\mu\text{g/liter}$) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|----------------|---------------|----------------|----------------|---------------|
| | April | June | July | August | October |
| Epi | 4.1 \pm 3.4 | 3.7 \pm 2.0 | 8.0 \pm 4.2 | 7.6 \pm 4.0 | 7.6 \pm 2.7 |
| N | (52) | (79) | (82) | (80) | (90) |
| Meta | (NA) | 4.1 \pm 3.4 | 8.8 \pm 4.4 | 16.5 \pm 6.2 | 6.5 \pm 3.1 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 4.5 \pm 5.6 | 5.2 \pm 3.0 | 10.0 \pm 5.0 | 7.8 \pm 6.4 | 4.8 \pm 2.4 |
| N | (113) | (99) | (123) | (100) | (108) |
| Nearshore | 9.0 \pm 10.0 | 6.4 \pm 4.4 | 10.3 \pm 7.1 | 7.8 \pm 3.7 | 9.5 \pm 3.8 |
| N | (18) | (22) | (22) | (23) | (20) |

Patterns in vertical structure of ammonia were apparent when the lake was thermally stratified. In August there was an obvious metalimnetic maximum in the vertical structure (Fig. 40). Maximum concentrations in this layer exceeded 20 $\mu\text{g/liter}$ at the three deep master stations in contrast to concentrations that were less than 5 $\mu\text{g/liter}$ at the surface. The August metalimnetic average was 16 $\mu\text{g/liter}$, also obviously much greater than either the epilimnetic or hypolimnetic cruise average for this month (Table 10). This pattern was not as evident during the July cruise, although there was a tendency for higher concentrations below the metalimnion. By October the subsurface maximum was no longer evident and, with the exception of Station 6, concentrations varied little from surface to bottom. The general pattern in

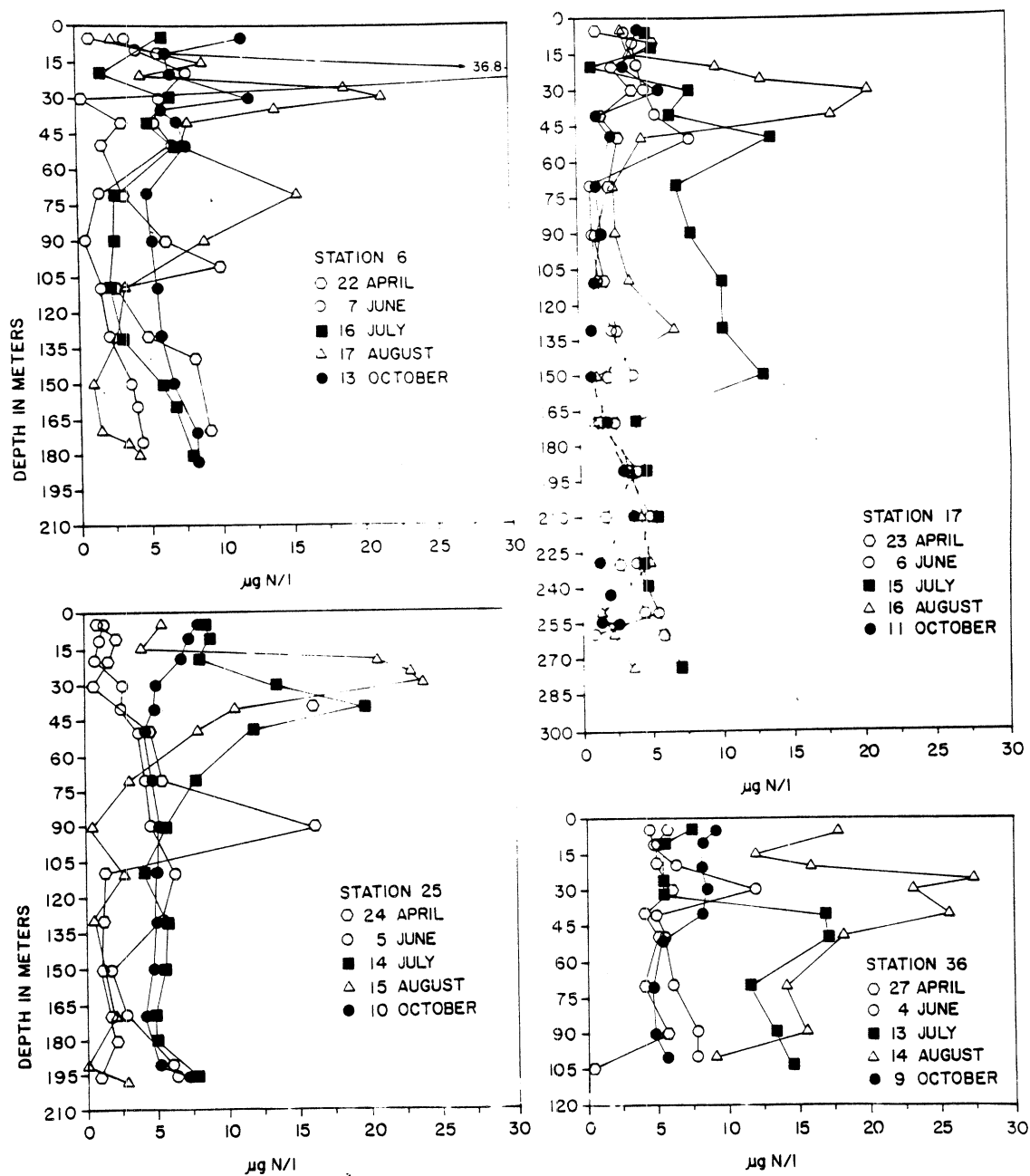


FIG. 40. Seasonal changes in ammonia nitrogen at master stations.

October appeared to be slightly higher concentrations in the epilimnetic waters than in the hypolimnion, with increased concentrations in the near-bottom waters. This general pattern of lower hypolimnetic concentration is suggested by the cruise means for October where epilimnetic and metalimnetic averages are greater than the hypolimnetic average (Table 10).

CHLORIDE

Average chloride concentrations ranged from 7.8 to 8.0 mg/liter among the open-lake strata sampled on the different cruises (Table 11). Data from the first cruise in April were much more variable than those obtained on subsequent cruises. Greater variability in April was probably the result of methodology and should not be attributed to environmental changes in concentration of this conservative substance.

Average concentrations for the July and October cruises show that chloride in the open lake averaged 8.0 mg/liter during 1976. Data in Table 11 suggest that chloride increased during the year. An increase in concentration would not be unexpected because there has been a long-term increase in chloride concentrations since the early 1900s (Beeton 1969).

TABLE 11. Seasonal changes in average chloride concentrations (mg/liter) for depth strata in offshore and nearshore waters. Data are means \pm one standard deviation. N indicates number of samples for each stratum. NA indicates no data could be assigned to stratum.

| Stratum | Cruise | | | | |
|-----------|-------------|-------------|-------------|-------------|-------------|
| | April | June | July | August | October |
| Epi | 7.89 + 0.52 | 7.81 + 0.09 | 8.00 + 0.10 | 7.95 + 0.10 | 8.01 + 0.15 |
| N | (54) | (79) | (82) | (80) | (90) |
| Meta | (NA) | 7.84 + 0.04 | 7.99 + 0.09 | 7.86 + 0.21 | 7.08 + 0.09 |
| N | (NA) | (3) | (41) | (65) | (27) |
| Hypo | 7.78 + 0.35 | 7.83 + 0.06 | 7.99 + 0.09 | 7.84 + 0.28 | 7.04 + 0.09 |
| N | (114) | (99) | (123) | (101) | (108) |
| Nearshore | 8.38 + 1.13 | 7.87 + 0.22 | 8.48 + 1.67 | 8.00 + 0.16 | 8.06 + 0.10 |
| N | (18) | (22) | (22) | (23) | (20) |

STRAITS OF MACKINAC

Twenty-five stations were established in the region west of the Straits of Mackinac. Included in this area are stations numbered from 41 to 65 located over a 70-km distance west of the Straits of Mackinac (Fig. 1). Environmental characteristics in this area change rapidly both temporally and spatially as the result of the interchange of water between Lake Michigan and Lake Huron (Saylor and Sloss 1976). Chemical and biological characteristics of the two lakes are different and the exchange and mixing of waters of the two lakes produce water masses with distinct chemical and biological characteristics (Schelske et al. 1976). Because variables vary spatially and temporally in the Straits of Mackinac region, we did not attempt to include Straits of Mackinac stations in the earlier presentations of spatial structure and seasonal changes.

Seasonal characteristics for data collected at the 5-m depth at the Straits of Mackinac stations have been summarized in Table 12. Variances for these 5-m samples tended to be larger than those associated with epilimnetic averages at main lake stations (Tables 2 to 11).

WATER TEMPERATURE

Seasonal patterns of surface temperatures at the Straits of Mackinac stations were similar to those for epilimnetic strata of the main lake stations. During April average water temperatures for both groups of stations were $<4^{\circ}\text{C}$ (Tables 2 and 12), indicating that the water column was not thermally stratified. In June, however, differences in average water temperatures were greatest. In the Straits area, the average temperature was

TABLE 12. Average concentrations for 5-m samples from the Straits of Mackinac stations. Data presented are means \pm one standard deviation. N is the number of samples for each cruise.

| Variable | April | | June | | July | | August | | October | |
|---------------------|---------------------------|------|---------------------------|------|---------------------------|------|---------------------------|------|---------------------------|------|
| | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| Temp. | 3.7 \pm 0.7 | | 10.8 \pm 0.9 | | 18.9 \pm 0.6 | | 18.7 \pm 2.3 | | 11.1 \pm 0.6 | |
| pH | | | 8.46 \pm 0.05 | | 8.20 \pm 1.30 | | 8.57 \pm 0.06 | | 8.44 \pm 0.04 | |
| NO ₃ -N | 186 \pm 10 | | 169 \pm 6.9 | | 144 \pm 11 | | 143 \pm 12 | | 179 \pm 14 | |
| NH ₃ -N | 5.3 \pm 13 | | 3.6 \pm 2.1 | | 6.9 \pm 1.3 | | 2.6 \pm 1.8 | | 6.7 \pm 1.5 | |
| SiO ₂ | 0.40 \pm 0.08 | | 0.28 \pm 0.08 | | 0.15 \pm 0.08 | | 0.22 \pm 0.08 | | 0.78 \pm 0.11 | |
| P. SiO ₂ | 0.54 \pm 0.09 | | 0.26 \pm 0.60 | | 0.38 \pm 0.10 | | 0.61 \pm 0.23 | | 0.63 \pm 0.13 | |
| Chlor. a | 2.76 \pm 0.47 | | 1.22 \pm 0.36 | | 0.81 \pm 0.14 | | 1.48 \pm 0.25 | | 1.62 \pm 0.19 | |
| TP | 6.0 \pm 1.3 | | 5.5 \pm 1.1 | | 8.6 \pm 5.6 | | 7.2 \pm 3.2 | | 7.4 \pm 2.1 | |
| TSP | 3.8 \pm 1.2 | | 2.73 \pm 0.40 | | 3.53 \pm 0.61 | | 2.86 \pm 0.82 | | 3.89 \pm 0.90 | |
| Cl | 7.14 \pm 0.43 N = 24 | | 7.13 \pm 0.39 N = 25 | | 7.44 \pm 0.27 N = 21 | | 7.40 \pm 0.39 N = 22 | | 6.89 \pm 0.32 N = 22 | |

10.8°C, compared to only 6.7°C for the main lake stations. The main reasons for colder temperatures at the main lake stations were that many of deep open-lake stations were homothermous and, in addition, the 7.3-m nearshore stations were excluded from open-lake averages. For the remainder of the year, temperatures were comparable for the two groups with the major difference being that the Straits stations averaged 3C° warmer in July than the main lake stations.

HYDROGEN ION CONCENTRATION

No pH data were obtained on the April cruise in the Straits of Mackinac area. On the remainder of the cruises there were only small differences in pH between the two groups of stations with the exception of the July cruise. In July the average pH in the Straits area was 8.20 \pm 1.30 (Table 12) compared to an epilimnetic average of 8.58 \pm 0.14 at the main lake stations (Table 3). Differences in averages for the other cruises were 0.05 pH units or less and, in fact, the averages and standard deviations for the August data were identical.

NITRATE NITROGEN

Comparing data for nitrate nitrogen from the Straits of Mackinac stations with those from the open lake indicate different seasonal cycles for the two areas of Lake Michigan. Seasonal changes for the Straits stations were smaller than in the open lake. Average concentrations showed a 0.043 mg/liter range for the Straits stations (Table 12), or less than half the 0.11 mg/liter range for the main lake stations (Table 4). Apparently the major factor for the smaller range at the Straits stations is shallower waters and, as a consequence, greater utilization of nitrate prior to sampling on the first

cruise. Most of the decrease in concentration at the open-lake stations occurred after thermal stratification or after the June cruise.

Nitrate concentrations at the open-lake stations were greater initially, but after thermal stratification decreased to lower levels (Table 4) than those found in the Straits of Mackinac (Table 12). Higher levels in the Straits in the summer may have resulted from subsurface flow and enrichment with high nitrate water from Lake Huron. Data collected in the summer and fall of 1973 from the Straits of Mackinac and northern Lake Huron (Schelske et al. 1976) show that hypolimnetic nitrate concentrations exceed 0.3 mg/liter. Therefore, subsurface transport from Lake Huron to Lake Michigan might enrich the epilimnetic Straits waters in terms of nitrate, which averaged 0.14 mg/liter during the summer (Table 12).

AMMONIA NITROGEN

Average concentrations of ammonia nitrogen ranged from 2.6 to 6.9 $\mu\text{g/liter}$ for the 5-m samples from the Straits region (Table 12). No discernible pattern was evident for averages from the five cruises. At open-lake stations average concentrations for the five cruises ranged from 3.7 to 8.0 $\mu\text{g/liter}$ (Table 5). Although averages appear to be greater for open-lake stations, they are probably not because of the large variances associated with most of the means. More than half of the standard deviations for the combined data sets are at least 50% of the mean.

SOLUBLE REACTIVE SILICA

Seasonal changes in silica concentrations were similar to those for nitrate in that the range in average concentrations was smaller for Straits of Mackinac stations than those for the open-lake epilimnion. However,

differences in the range for silica were 0.63 mg/liter for the Straits stations (Table 12), and 0.77 mg/liter for the open-lake stations (Table 6), relatively small differences compared to a greater than two-fold difference in averages for nitrate concentrations. Undoubtedly, the main reason for smaller differences in silica was the fact that average concentrations in both areas were reduced by diatom growth to 0.2 mg/liter, a level below which diatom growth would be severely limited. Uptake of nitrogen by phytoplankton was not limited by supplies in the water so greater ranges in concentration resulted from phytoplankton uptake and growth.

Seasonal patterns in average concentrations were also different for the two areas. In the Straits region, average concentrations in April were 0.40 mg/liter (Table 12), compared to 0.96 mg/liter at the open stations (Table 6). During the October cruise, concentrations at the Straits stations were greater than at any time sampled, whereas in the open lake the average epilimnetic concentration was only 0.45 mg/liter. The more rapid reduction in silica concentrations in the spring, like that for nitrate, is probably an effect that can be attributed to shallower water in the Straits region.

PARTICULATE SILICA

Seasonal cycles of particulate silica were not evident for data obtained either from the Straits or open-lake stations. Large variances were associated with most of the means which indicates complex spatial structure for this variable. The largest means for particulate silica were obtained from the Straits stations, particularly for the cruises in April, August, and October when the average concentrations ranged from 0.54 to 0.63 mg/liter (Table 12). At the open-lake stations, largest means were found for the

April, June, and July cruises when average concentrations ranged from 0.40 to 0.49 mg/liter (Table 7). In August and October when averages for the open-lake stations were smallest, average particulate silica concentrations at the Straits of Mackinac stations were greatest. Generally higher concentrations of particulate silica in the Straits area indicate that silica limitation of diatom growth that occurs in the open lake during late summer and early fall is at least partially relaxed in the Straits area. Presumably this relaxation is at least partially the result of entrainment of silica-rich hypolimnetic water from Lake Huron in the epilimnetic waters of the Straits area.

CHLOROPHYLL a

Ranges in epilimnetic chlorophyll concentrations in the Straits area were comparable to those found for open-lake stations. In the Straits area a somewhat typical seasonal cycle was observed with the largest average concentration (2.76 $\mu\text{g/liter}$) occurring in April (Table 12). The smallest average concentration (0.81 $\mu\text{g/liter}$) was found in August and then the average concentration increased to 1.62 $\mu\text{g/liter}$ in October. At the open-lake stations, the greatest average concentration (2.2 $\mu\text{g/liter}$) was found in April and the average concentrations decreased each month to the smallest average (0.90 $\mu\text{g/liter}$) in October (Table 8). Seasonal patterns for the two areas therefore obviously were very different.

TOTAL PHOSPHORUS

Total phosphorus (TP) concentrations in the Straits region varied little among the five cruises. Average concentrations ranged from 5.5 to 8.6 $\mu\text{g/liter}$ with no obvious difference in patterns of concentrations among the different sampling dates (Table 12). In fact, there are no statistically

significant differences among the mean concentrations for the five cruises. On the average, concentrations in the Straits area were smaller, but not statistically different, than those for the epilimnetic strata at the open-lake stations where concentrations ranged from 6.8 to 8.9 $\mu\text{g/liter}$ (Table 9). These results would indicate that average TP concentrations were slightly greater in the open lake than in the Straits region. This is the relationship that would be expected from mixing Lake Michigan water with Lake Huron water that has smaller phosphorus concentrations.

TOTAL SOLUBLE PHOSPHORUS

Averages for total soluble phosphorus (TSP) concentrations were less variable than average TP concentrations (Table 12). Ranges for average TSP concentrations were 2.7 to 3.9 $\mu\text{g/liter}$ for the Straits stations, and 3.4 to 4.7 $\mu\text{g/liter}$ for the open-lake stations (Table 10). Although there was overlap in the averages for the two groups of stations, cruise means for each of the five cruises was greater for the open-lake stations than for the Straits stations. Like data for TP, these results indicate, as expected, that phosphorus concentrations in the open lake were greater than those in the Straits area. Lower averages for the Straits stations were expected because Lake Michigan water is diluted in the Straits area by intrusion of Lake Huron water with lower phosphorus concentrations.

CHLORIDE

Average concentrations of chloride for the Straits of Mackinac are obviously less than those for the open-lake stations. Average concentrations for the Straits stations ranged from 6.9 to 7.4 mg/liter (Table 12), whereas the average concentrations for open-lake stations ranged from 7.8 to 8.0 mg/

liter (Table 11). Smaller concentrations in the Straits area undoubtedly result from intrusion of Lake Huron water with an average chloride concentration in 1974 of 5.4 mg/liter (IJC 1977, p. 410), about 2.5 mg/liter less than the 1976 average concentration for northern Lake Michigan (Table 11).

Two obvious spatial differences can be seen from the collected data. First, Straits of Mackinac stations (Table 12) were different in some respects from stations in the open part of the lake (Tables 2 to 11), and second, nearshore stations also differed from those in the open part of the lake. There were differences between Straits of Mackinac stations and open-lake stations in epilimnetic averages of data for water temperature, pH, and ammonia nitrogen (Table 12). Nitrate nitrogen and silica averages were smaller for the April, June, and July samples from the Straits stations, but in July and August averages were smaller for the open-lake stations. These differences were attributed to shallower water that stratified earlier at the Straits of Mackinac area and intensified photoplankton utilization of nutrients, and to the inflow of subsurface water from Lake Huron which supplied nitrate and silica-rich water to the epilimnetic water of the open-lake stations after thermal stratification was established. Greater soluble silica concentrations in August and October in the Straits of Mackinac were associated with particulate silica concentrations that were nearly twice as large as those for the open-lake (Table 12). These larger standing crops of diatoms would be expected to result from the enrichment of open-lake silica-limited waters with silica-rich waters from Lake Huron.

Differences in chlorophyll a concentrations between the Straits of Mackinac and open-lake stations probably also resulted from seasonal

differences in the thermal cycle and timing of thermal stratification. The average standing crop of 2.8 μg chlorophyll a/liter in April for the Straits stations was the largest cruise mean obtained, but epilimnetic means of 2.2 and 2.1 μg /liter were obtained for April and June in the open lake. Given the large variances, there are no differences among these means.

Epilimnetic averages of total phosphorus and total soluble phosphorus for open-lake stations were greater on each of the five cruises than those for the Straits of Mackinac stations. The differences are not statistically significant if the usual statistical tests are utilized; however, the fact that the open-lake stations have greater averages for all 10 pairs of data than the Straits stations indicates that the differences are real. Greater concentrations would be expected in Lake Michigan because water in the Straits is diluted with Lake Huron water that has an average total phosphorus concentration of 5 μg P/liter (IJC 1976) compared to an average of 8 μg P/liter or more for open Lake Michigan (Table 8).

The most obvious difference between the Straits of Mackinac and open-lake stations is in chloride concentrations. Epilimnetic averages for the open-lake stations only ranged from 7.9 to 8.0 mg/liter in comparison to averages for the Straits stations which ranged from 6.9 to 7.4 mg/liter. Lower averages in the Straits samples result from entrainment and mixing of Lake Huron water, which in 1974 had an average chloride concentration of 5.4 mg/liter (IJC 1976), with open Lake Michigan water. Mixing of water masses in the Straits area is evident from the chloride data because, with the exception of the first cruise when there were methodological problems with chloride analysis, standard deviations for the Straits stations are three to four times greater than those for the open-lake stations (Tables 11 and 12).

Average conditions at the nearshore stations differed in certain respects with those for epilimnetic samples from the offshore stations. However, in general these differences were relatively small, with the exception of chlorophyll concentrations in April and June when offshore waters were not stratified. Average nearshore chlorophyll a concentrations in April and June were 7.2 and 3.4 $\mu\text{g/liter}$ compared to open-lake averages of 2.2 and 2.1 $\mu\text{g/liter}$. Larger nearshore averages probably resulted from greater phosphorus supplies and from the fact that the nearshore waters stratified sooner and, as a consequence, had greater water temperatures in April and June than the offshore waters. Another result of larger nearshore standing crops was that silica and nitrate concentrations in April and June were much lower in the nearshore than in the open-lake epilimnion.

Although there may be large differences between nearshore and open-lake conditions, the significance of these differences depends on the problems or questions of interest (Schelske 1980). Tributary inputs of nutrients, particularly phosphorus, that produce larger nearshore phosphorus and chlorophyll a concentrations than are found in the open waters obviously affect nearshore water quality and eventually impact the open lake if large inputs continue over a long period. However, larger concentrations of materials near shore affect lake-wide average concentrations of nutrients very little. The effect is small because the nearshore volume (less than 40 m deep) is a relatively small fraction, about 5%, of the total lake volume (Schelske 1980). It can be seen from the hypsographic curve of Lake Michigan that the cumulative area of the lake increases much more rapidly than the volume and that the 25% of the nearshore lake surface only accounts for 5% of the total volume (Fig. 41). Therefore, for comparison of long-term trends, it

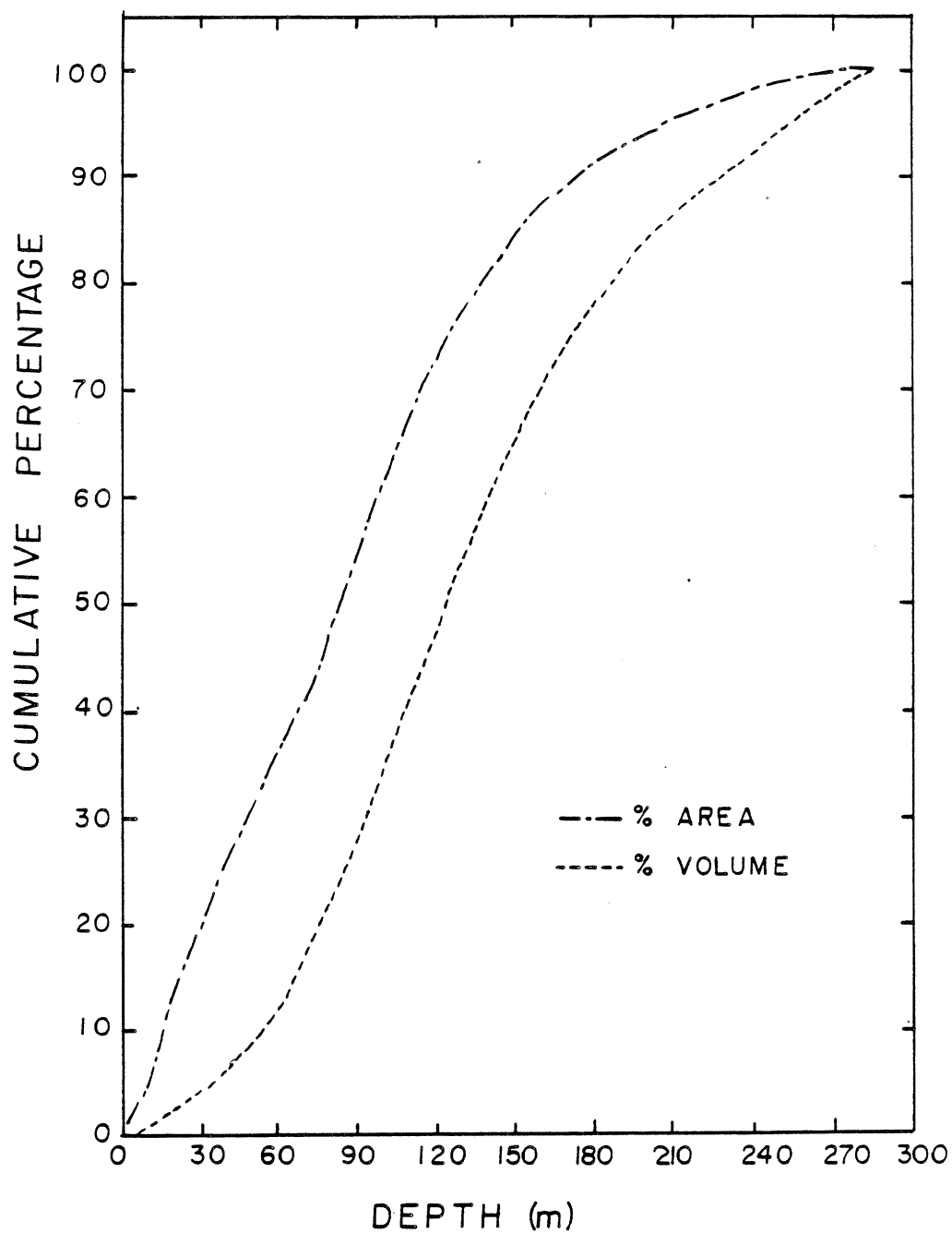


FIG. 41. Hypsographic curve of Lake Michigan as cumulative percent of area and volume (from Long and Schueler 1968).

is essential to obtain data that represent open-lake conditions and it is relatively unimportant to obtain data on the nearshore environment.

Greater differences between nearshore and offshore conditions were reported previously (Table 13) than were found for the present study (Tables 2-11). In the previous studies greater ranges resulted because data from southern basin nearshore areas as well as data from nearshore areas near large sources of tributary loading were included. Studies that show greater enrichment and standing crops of phytoplankton in the nearshore and southern basin of the lake than in the northern basin of the lake have been reviewed and discussed by Tarapchak and Stoermer (1976).

The purpose of the present study was not to analyze long-term trends in different variables. Establishing long-term trends is difficult for variables other than the conservative parameters because the historical data are limited and of questionable quality (see Schelske et al. 1980). In addition, data on phosphorus and chlorophyll a vary seasonally and have large variances associated with them (Tables 7, 9) which complicate attempts to determine trends in concentrations.

It is perhaps of interest, however, to show how average conditions in the open waters of Lake Michigan differ from those in Lake Superior and Lake Huron which are more oligotrophic and in Lake Erie and Lake Ontario which are more eutrophic. The major differences between the upper lakes and Lake Ontario and Lake Erie is that the lower lakes have several times greater average chlorophyll a and total phosphorus concentrations (Table 14). In addition, the summer minimum in nitrate nitrogen concentration is lowest in Lake Erie. Nitrate concentrations in the summer are reduced more in the lower lakes because they produce the largest standing crop of phytoplankton and

TABLE 13. Representative values for physical-chemical variables in offshore and nearshore waters of Lake Michigan. Range, with the exception of data for total phosphorus and total alkalinity, is due to seasonal cycles.† Nearshore zone is with the 40-m contour.

| | Offshore | Nearshore |
|---|---------------------|-----------|
| Temperature (°C) | 0.1-24 | 0.1-24 |
| pH | 8.1-9.0 | 7.9-9.1 |
| Total alkalinity (meq/liter) | 2.04-2.17 | 2.06-2.23 |
| NO ₃ -N (mg/liter) | 0.10-0.28 | 0.010-1.0 |
| NH ₃ -N (mg/liter) | <0.025 | |
| SiO ₂ (mg/liter) | <0.1-1.4 | <0.1-3.0 |
| Total P (μg/liter) | 5-10 | 15-150 |
| Chlorophyll <u>a</u> (mg/m ³) | 0.7-2.7*, 1.0-4.5** | 2-> 20 |

*Ladewski and Stoermer (1973).

**Rousar (1973).

†From Schelske et al. 1980.

chlorophyll a which requires nitrate nitrogen. The maximum nitrate concentrations in the upper lakes are similar, but the range is greatest for Lake Michigan which produces the largest standing crop of chlorophyll a. Likewise, silica levels are reduced to limiting concentrations in Lake Michigan but not in the other upper Great Lakes and the range in seasonal difference increases with total phosphorus concentrations (Schelske 1975). Silica concentrations in the lower lakes are low, indicating that diatoms grow under silica concentrations that are limiting or near limiting for diatom growth throughout the year. A concentration of 0.37 mg SiO₂/liter has been considered as rate limiting for diatom growth in Lake Michigan (Parker et al. 1977) based on the work of Kilham (1975).

TABLE 14. Maximum total phosphorus and chlorophyll a concentrations and seasonal changes in silica and nitrate nitrogen concentrations in the Great Lakes. Data for the early 1970s and are summarized from Weiler (1980), Schelske et al. (1980), IJC (1976), and Dobson et al. (1974).

| Lake | Maximum Total P ($\mu\text{g P/L}$) | Maximum Chlorophyll <u>a</u> ($\mu\text{g/L}$) | Seasonal Differences | |
|----------|---|--|--|--------------------------------|
| | | | Silica ($\text{mg SiO}_2/\text{L}$) | Nitrate (mg N/L) |
| Ontario | 25 | 8-9 | 0.1-0.5 | 0.04-0.28 |
| Erie, EB | 25 | 7-8 | <0.1-0.3 | 0.02-0.18 |
| Erie, CB | 30 | 10-11 | <0.1-0.3 | 0.02-0.14 |
| Michigan | 8 | 3-4 | 0.1-1.4 | 0.10-0.28 |
| Huron | 5 | 2 | 1.1-1.9 | 0.21-0.26 |
| Superior | 4 | 1 | 2.3-2.4 | 0.23-0.28 |

The comparison of conditions in the upper lakes with those in the lower lakes shows a large difference in average concentrations of total phosphorus and chlorophyll a. There are two points of importance about the difference in concentrations. First, the total phosphorus concentration is large in Lake Ontario, and a reduction in average concentration of 6 $\mu\text{g P/liter}$ or more has occurred there since 1974-76 as the result of phosphorus control measures. This reduction is more than the total phosphorus concentration in either Lake Superior or Lake Huron (Table 14). Second, average total phosphorus concentrations among the three upper lakes vary only from 4 to 8 $\mu\text{g P/liter}$. However, there are definite biological changes that apparently have resulted from the relatively small amount of phosphorus enrichment of Lake Huron and Lake Michigan compared to Lake Superior. Silica depletion which occurs in Lake Michigan but not in Lake Huron or Lake Superior is the result of

increased diatom growth and phosphorus enrichment (Schelske and Stoermer 1971).

Several points should be made about the design of studies on Lake Michigan. First, nearshore conditions differ from those in offshore waters, particularly in the southern part of the lake. Second, because of disproportionate nearshore loading (Schelske 1980), the effects of nutrient enrichment are most obvious in the nearshore areas that are influenced by tributary and other nearshore nutrient sources. Third, even among stations that might be considered offshore, there are distinct differences in chemical characteristics. General conditions at stations to the west of the Straits of Mackinac may be affected by inflow of water from Lake Huron, and phasing of seasonal changes is affected by water depth. Station 36 consistently had different characteristics than the other three master stations, an effect which was attributed to this being the shallowest station. Because the station was shallow, the water column stratified earlier and surface conditions changed rapidly in comparison to deep stations. Fourth, sampling strategies must reflect temporal and spatial scales that depend on the variable and problem of interest. For example, long-term or year-to-year changes in chloride can be detected with relatively little spatial and temporal sampling compared to that which would be necessary to detect differences in total phosphorus concentrations. Chloride concentrations averaged 8 mg/liter in 1976 (Table 11), possibly four times greater than in 1900 (Beeton 1969). The relative change in total phosphorus since 1900 has probably been less than a four-fold change. Determining changes in total phosphorus concentrations is complicated by seasonal and spatial variability and by large variances in cruise averages. The source or sources of

variability have not been studied adequately. Finally, the implication underlying the above points is that sampling strategies must be designed for specific purposes. This is not to say that sampling for every study should be undertaken separately. In fact, if costs and logistics of obtaining data are considered, multiple purpose studies may be highly desirable and cost effective.

REFERENCES

- Ayers, J. C., E. F. Stoermer, and P. McWilliams. 1967. Recently notified changes in the biology-chemistry of Lake Michigan, pp. 95-111. In J. C. Ayers and D. C. Chandler, Studies on the environment and eutrophication of Lake Michigan. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 30.
- Bartone, C. R., and C. L. Schelske. 1982. Lake-wide seasonal changes in limnological conditions in Lake Michigan in 1976. J. Great Lakes Res. 8: 413-427.
- Beeton, A. M. 1969. Changes in the environment and biota of the Great Lakes, pp. 150-187. In Eutrophication: causes, consequences, correctives. Nat. Acad. Sci., Washington, D.C.
- Chapra, S. C. 1977. Total phosphorus model for the Great Lakes. J. Environ. Eng. Div. 103: 147-161.
- Conway, H. L., J. I. Parker, E. M. Yaguchi, and D. L. Mellinger. 1977. Biological utilization and regeneration of silicon in Lake Michigan. J. Fish. Res. Board Can. 34: 537-544.
- Davis, C. O., and M. S. Simmons. 1979. Manual for field and laboratory procedures. Spec. Rep. No. 70, Great Lakes Research Division, University of Michigan. Pages unnumbered.
- Dobson, H. F. M., M. Gilbertson, and P. G. Sly. 1974. A summary and comparison of nutrients and related water quality in Lakes Erie, Ontario, Huron, and Superior. J. Fish. Res. Board Can. 31: 731-738.
- Gannon, J. E. 1972. A contribution to the ecology of zooplankton Crustacea of Lake Michigan and Green Bay. Unpubl. Ph.D. thesis, Univ. Wisconsin. 257 pp.
- International Joint Commission. 1976. The waters of Lake Huron and Lake Superior. Vol. I, Summary and recommendations. Report to IJC by Upper Lakes Reference Group, Windsor, Ontario. 236 pp.
- _____. 1977. The waters of Lake Huron and Lake Superior. Vol. II. (Part B), Lake Huron, Georgian Bay and the North Channel. Report to IJC by Upper Lakes Reference Group, Windsor, Ontario. pp. 295-743.
- Kilham, S. S. 1975. Kinetics of silicon-limited growth in the freshwater diatom Asterionella formosa. J. Phycol. 11: 396-399.
- Ladewski, T. B., and E. F. Stoermer. 1973. Water transparency in southern Lake Michigan in 1971 and 1972. In Proc. 16th Conf. Great Lakes Res., pp. 791-807. Internat. Assoc. Great Lakes Res.

- Long, M., and R. L. Schueler. 1968. Depth-area relationships of the Laurentian Great Lakes in comparison to their commercial fisheries productivity. Unpublished manuscript of paper presented at the April 17-19, 1968 meeting of the Midwest Benthological Society, Madison, Wisconsin.
- Menzel, D. W., and N. Corwin. 1965. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. *Limnol. Oceanogr.* 10: 280-282.
- Mortonson, J. A., and A. S. Brooks. 1980. Occurrence of a deep nitrite maximum in Lake Michigan. *Can. J. Fish. Aquat. Sci.* 37: 1025-1027.
- Parker, J. I., H. L. Conway, and E. M. Yaguchi. 1977. Seasonal periodicity of diatoms, and silicon limitation in offshore Lake Michigan, 1975. *J. Fish. Res. Board Can.* 34: 552-558.
- Riemann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. *Limnol. Oceanogr.* 23: 1059-1066.
- Rockwell, D. C., D. S. DeVault III, M. F. Palmer, C. V. Marion, and R. J. Bowden. 1980. Lake Michigan Intensive Survey 1976-1977. Great Lakes National Program Office. U.S. Environmental Protection Agency, Chicago, IL. 154 pp. plus Appendix.
- Rousar, D. C. 1973. Seasonal and spatial changes in primary production and nutrients in Lake Michigan. *Water, Air, Soil Pollut.* 2: 497-514.
- Saylor, J. H., and P. W. Sloss. 1976. Water volume transport and oscillatory current flow through the Straits of Mackinac. *J. Physical Oceanogr.* 6: 229-237.
- Schelske, C. L. 1975. Silica and nitrate depletion as related to rate of eutrophication in Lakes Michigan, Huron, and Superior, pp. 277-298. In A. D. Hasler (ed.), *Coupling of land and water systems*. Springer-Verlag New York Inc., New York.
- _____. 1980. Dynamics of nutrient enrichment in large lakes, the Lake Michigan case. *Proceedings of the International Symposium for Inland Waters and Lake Restoration*, held in Portland, Maine, Sept. 8-12, 1980. U.S. Environmental Protection Agency.
- _____, and E. Callender. 1970. Survey of phytoplankton productivity and nutrients in Lake Michigan and Lake Superior. In *Proc. 13th Conf. Great Lakes Res.*, pp. 93-105. *Internat. Assoc. Great Lakes Res.*
- _____, and E. F. Stoermer. 1971. Eutrophication, silica and predicted changes in algal quality in Lake Michigan. *Science* 173: 423-424.

- _____, E. F. Stoermer, J. E. Gannon, and M. S. Simmons. 1976. Biological, chemical and physical relationships in the Straits of Mackinac. Ecol. Res. Series, U.S. Environmental Protection Agency, Duluth, Minnesota, Rep. No. EPA-600/3-76-095. 266 pp.
- _____, L. E. Feldt, and M. S. Simmons. 1980. Phytoplankton and physical-chemical conditions in selected rivers and the coastal zone of Lake Michigan, 1972. Univ. Michigan, Great Lakes Res. Div. Pub. No. 19. 162 pp.
- Simmons, M. S. 1980. Routine determination of particulate silica in water. Anal. Letters 13: 67-74.
- Stoermer, E. F. 1972. Statement, pp. 217-254. In Conf. Pollution of Lake Michigan and its tributary basin, Illinois, Indiana, Michigan, and Wisconsin - 4th session, Sept. 19-21, 1972, Chicago, Illinois. U.S. Environmental Protection Agency. Vol. I.
- _____, and J. J. Yang. 1969. Plankton diatom assemblages in Lake Michigan. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 47. 268 pp.
- Strickland, J. D. H., and T. R. Parsons. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Canada No. 167. 311 pp.
- Tarapchak, S. J., and E. F. Stoermer. 1976. Phytoplankton of Lake Michigan, pp. 1-211. In Environmental Status of the Lake Michigan region, Vol. 4. Argonne Nat. Lab., Argonne, Illinois, ANL/ES-40.
- Weiler, R. R. 1980. Chemistry of the North American Great Lakes. Verh. Internat. Verein. Limnol. 21: 1681-1694.

LIMNOLOGICAL CHARACTERISTICS OF
NORTHERN LAKE MICHIGAN, 1976

Part 2. Phytoplankton Population Studies

by

Eugene F. Stoermer

INTRODUCTION

In this section we summarize phytoplankton abundance and distribution patterns within the area of interest. The distribution patterns of abundant specific populations and composite groups have been plotted. A complete listing of all populations encountered and summary information concerning their abundance is contained in Appendix I. The complete numerical data set, in computer compatible format, was transferred to the sponsoring agency project officer (Mr. Nelson Thomas), as required, and should be available from USEPA.

When studying an area as large as northern Lake Michigan, it is necessary to reach a reasonable compromise between areal coverage and desirable sample density in areas of special interest, where strong gradients may exist. In this study we have analyzed samples from the same stations taken for chemical and physical measurements. Because previous work has indicated that the region near the Straits of Mackinac was somewhat atypical of the rest of the lake (Schelske et al. 1976), sample density was increased in this region. The other region of special interest in northern Lake Michigan is Green Bay. Because of severe eutrophication problems, Green Bay has been more intensively studied than the offshore waters of the lake. Data comparable to those presented here have been developed for Green Bay as part of another study (Stoermer and Stevenson 1980).

MATERIALS AND METHODS

Samples were taken as 125-mL splits from Niskin Bottle casts, fixed in glutaraldehyde for a minimum of 4 hr at 4°C in the dark, and prepared as semi-

permanent microscope slides by the membrane filter clearing technique (Schelske et al. 1976).

Slides were analyzed by enumeration of taxa which occurred on replicate transects of the prepared slides. Count data were encoded and subsequent calculations of population density estimates and graphic representations of population density distributions were produced using a locally developed biological data base management system (FIDO). Distribution patterns of most abundant taxa are shown in subsequent sections of this report and a summary of the occurrence of all taxa recorded is provided in Appendix I. Original data are available in hard copy and computer compatible format (magnetic tape) in this laboratory.

PHYTOPLANKTON DISTRIBUTION IN NEAR SURFACE WATERS

Total phytoplankton abundance in the near-surface waters (Fig. 42) was low in April, with maximum densities at stations near shore and in relatively shallow water in the Straits region. There appears to be a north-south differentiation due to earlier development of the thermal bar at inshore stations on the southern transect. Relatively high phytoplankton abundances tend to follow the outward excursion of the thermal bar at stations sampled during the June cruise. In July, phytoplankton abundance was relatively uniform across the lake, with a trend toward higher values in the southern part of the sampling area. Phytoplankton abundance declined at most stations by August, but relatively high abundances were present at stations along the western shore which may be influenced by discharges from Green Bay. Phytoplankton abundance also increased in the Straits area, perhaps as a result of nutrient replenishment by the Lake Huron counter flow.

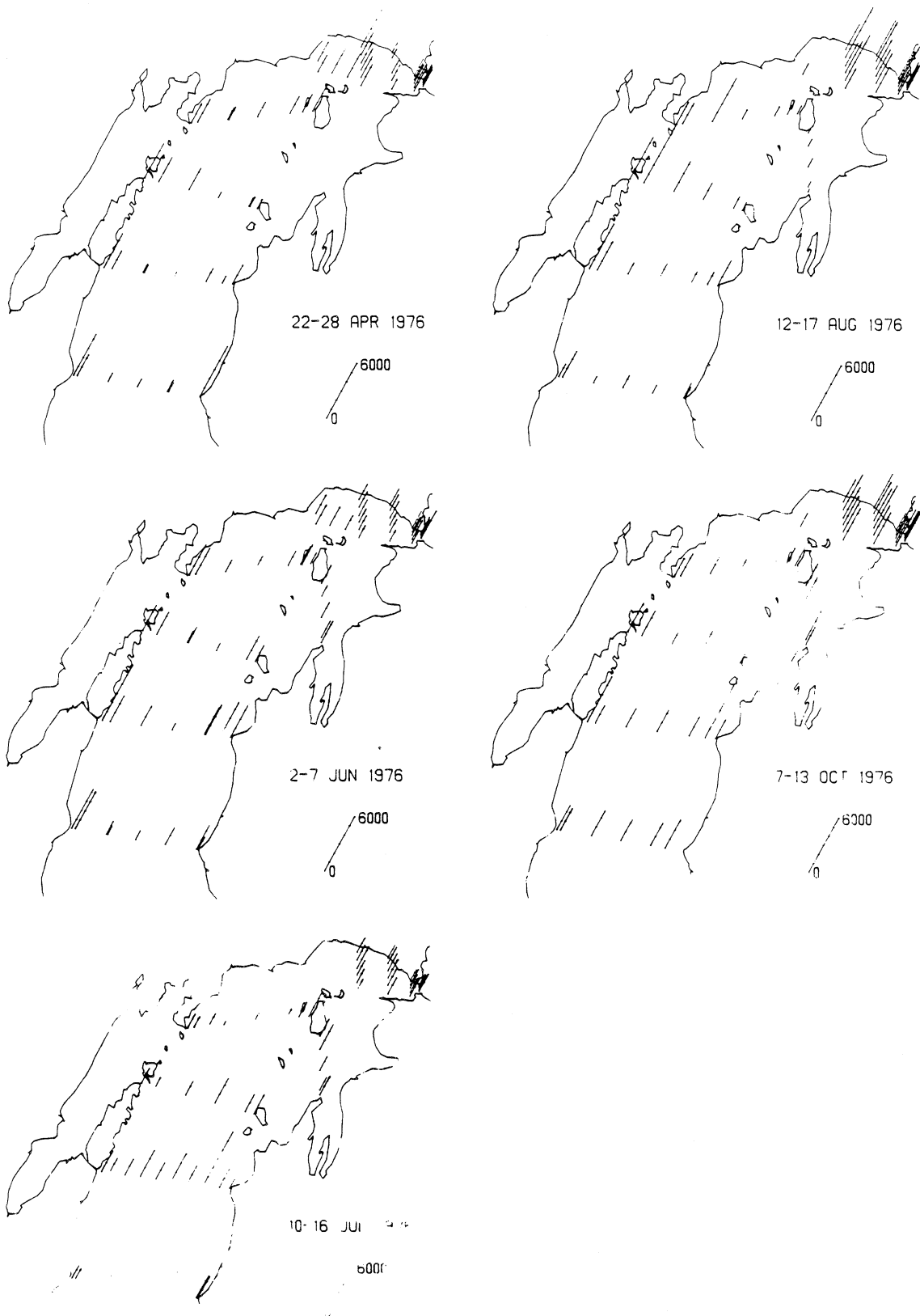


FIG. 42. Seasonal distribution and abundance trends of the total phytoplankton assemblage (cells/mL).

Phytoplankton abundance increased in October, particularly at southern stations, probably as a result of nutrient replenishment resulting from down-mixing to the thermocline.

Total diatom abundance (Fig. 43) followed the same general pattern as total phytoplankton abundance during April, June, and July. Following complete stratification and silica depletion in the surface waters, the abundance of this group was severely depressed except at nearshore stations and stations in the Straits region where nutrient resupply allowed continued growth. A slight increase in diatom abundance was noted in October, probably as a result of nutrient resupply from thermocline depression.

Most species of Achnanthes (Fig. 44) are primarily benthic organisms and significant occurrences in plankton samples are an index of benthic entrainment or entrainment from river sources. Small populations were found at stations in the Straits area and at nearshore stations on all cruises. An anomalously high abundance of members of this genus was found at Station 67, near Beaver Island, on the July cruise.

Members of the genus Amphora (Fig. 45) are also primarily benthic. Although somewhat less abundant than Achnanthes, they followed the same general distribution pattern, including very high values at Station 67 in July. They were also unusually abundant at stations near Rawley Point on all sampling dates.

Asterionella formosa Hass. (Fig. 46) is a widely distributed and apparently eurytopic species. It reached highest abundance at Station 10 near Big Sable Point in April, but was more generally abundant during July. Unlike some of the other diatom species, significant populations were noted

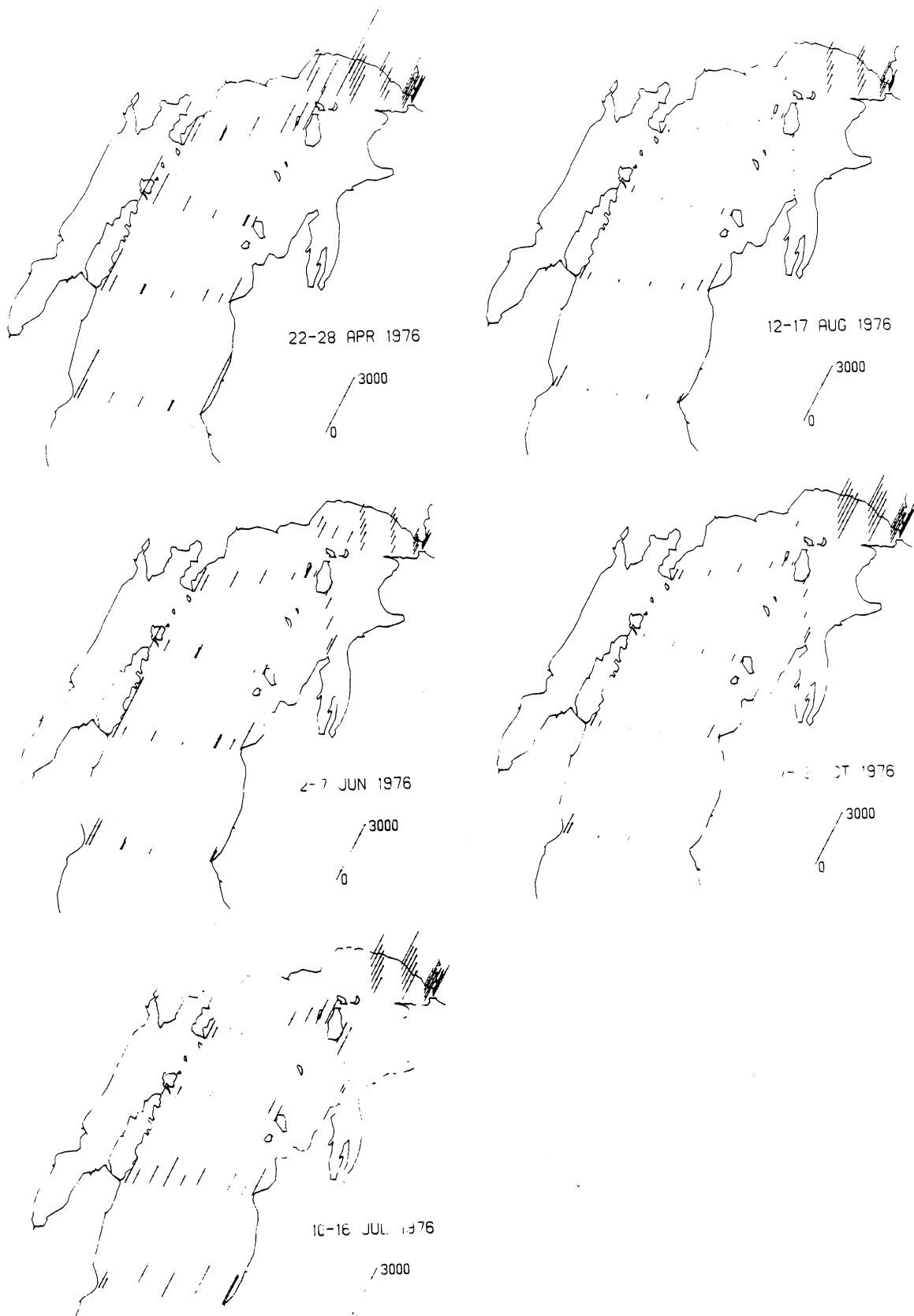


FIG. 43. Seasonal distribution and abundance trends of diatoms.

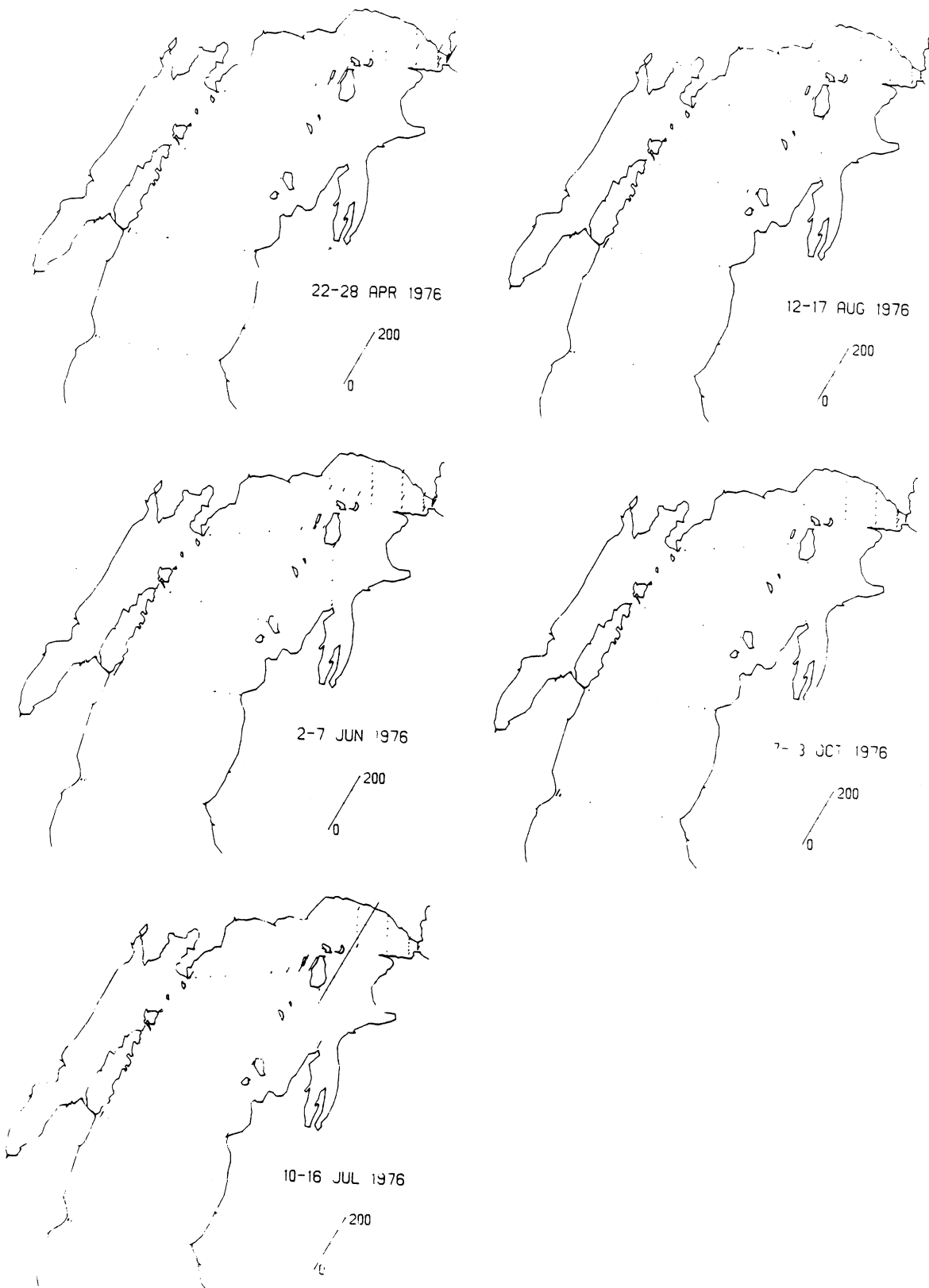


FIG. 44. Seasonal distribution of the genus Achnanthes.

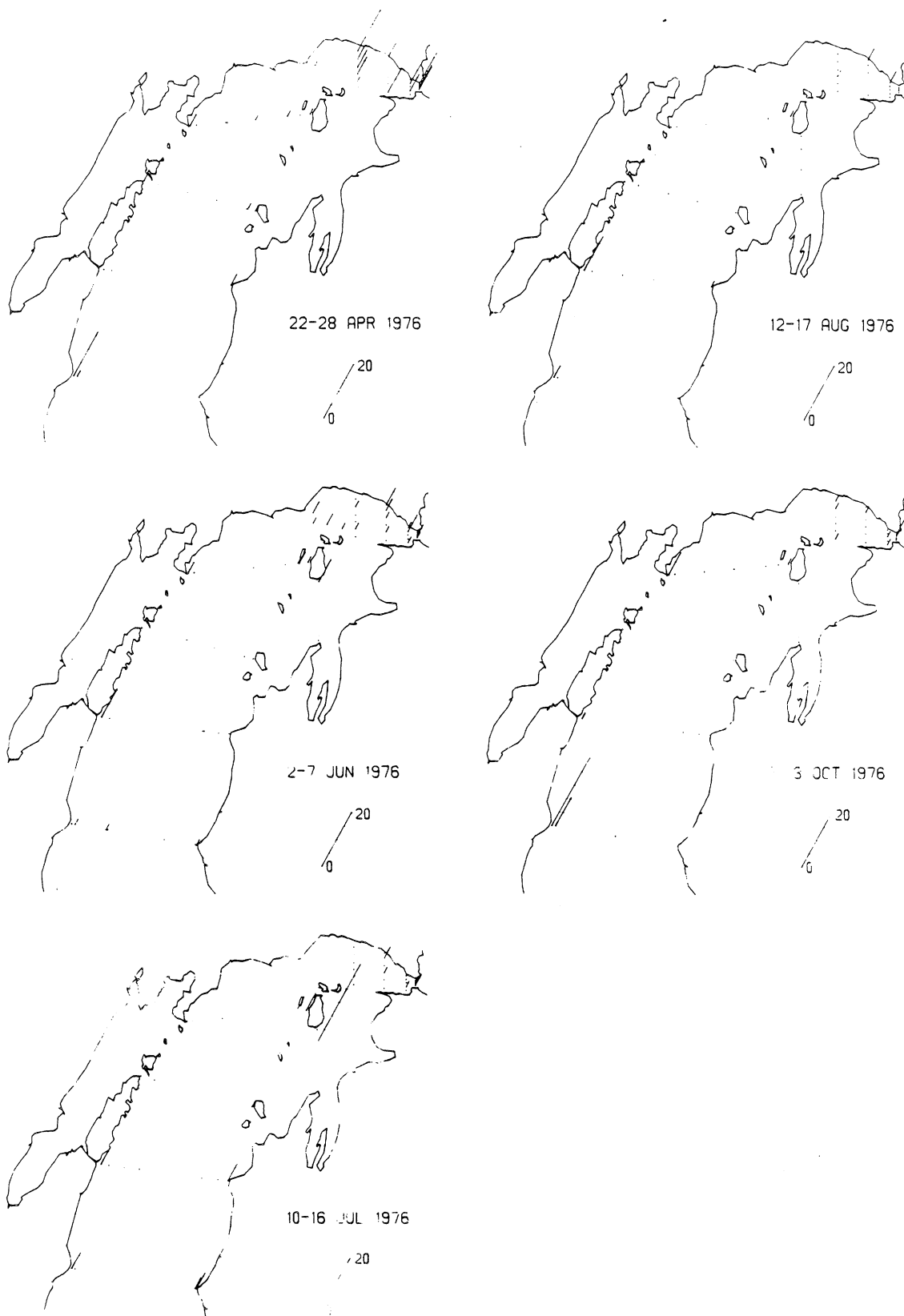


FIG. 45. Seasonal distribution of the genus Amphora.

throughout the summer, particularly at stations near shore which may have been supplied with added nutrients from upwelling or shoreline sources.

Cyclotella comensis Grun. is a species which has not been historically abundant in Lake Michigan. In recent years it has become a major dominant in Lake Huron and occurs in bloom quantities during the summer in areas such as Thunder Bay and the Saginaw Bay interface which receive significant nutrient inputs (Stoermer and Kreis 1980). Based on Stoermer and Kreis's observations, it is able to utilize silica at particularly low levels and has a relatively high nitrate requirement. In northern Lake Michigan it was particularly abundant at stations in the Straits area, although populations were found at most stations sampled during July, August, and October (Fig. 47).

Cyclotella comta (Ehr.) Grun. previously was a dominant population at offshore stations throughout the lake during the summer (Stoermer and Yang 1969). During this study the only abundant occurrences noted came from stations in the Straits area, although isolated populations were found throughout the region sampled during July (Fig. 48). This species is one of the oligotrophic populations which are characteristically eliminated by eutrophication in the Great Lakes (Hohn 1969).

Cyclotella ocellata Pant. is another member of the characteristically oligotrophic Cyclotella flora (Hutchinson 1967). In the modern Great Lakes significant populations are usually found in surface waters only during circulation periods. It remains abundant in the subthermocline phytoplankton maximum and its appearance after stratification has become established is a good indicator of upwelling. In northern Lake Michigan it was present at most stations sampled during the first three cruises, although abundance was reduced at stations near Green Bay. In August it was present only in apparent

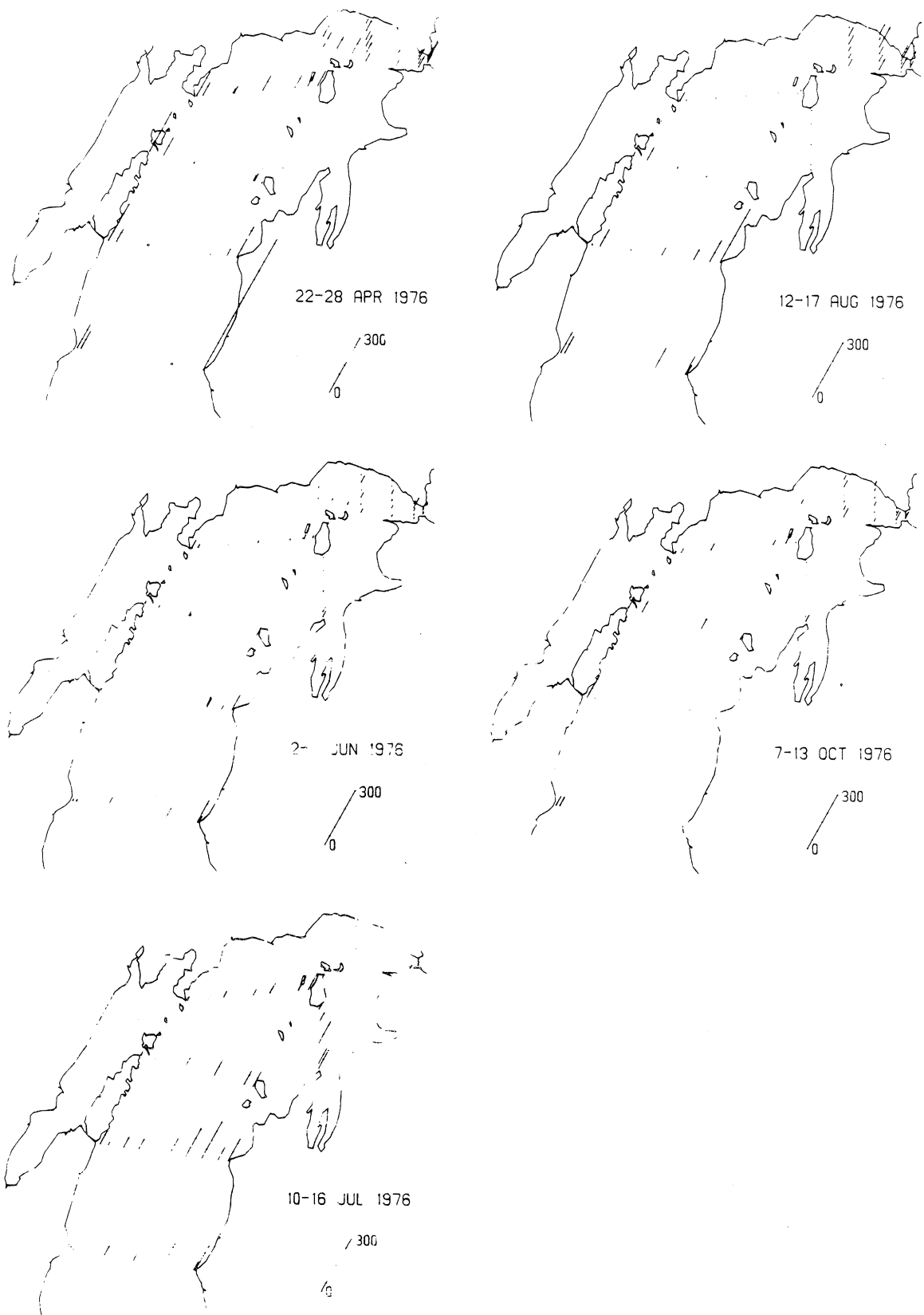


FIG. 46. Seasonal distribution of Asterionella formosa.

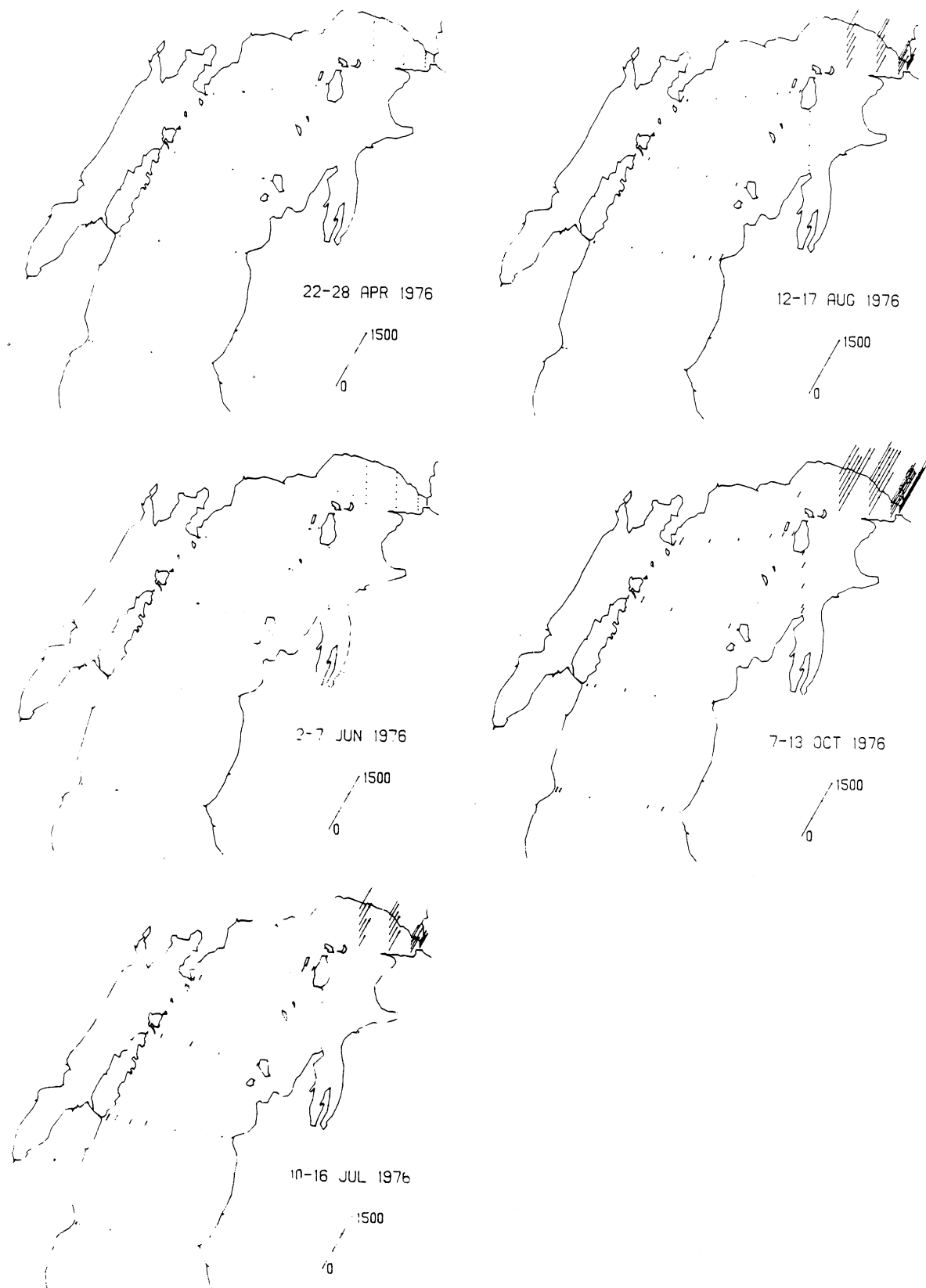


FIG. 47. Seasonal distribution of Cyclotella comensis.

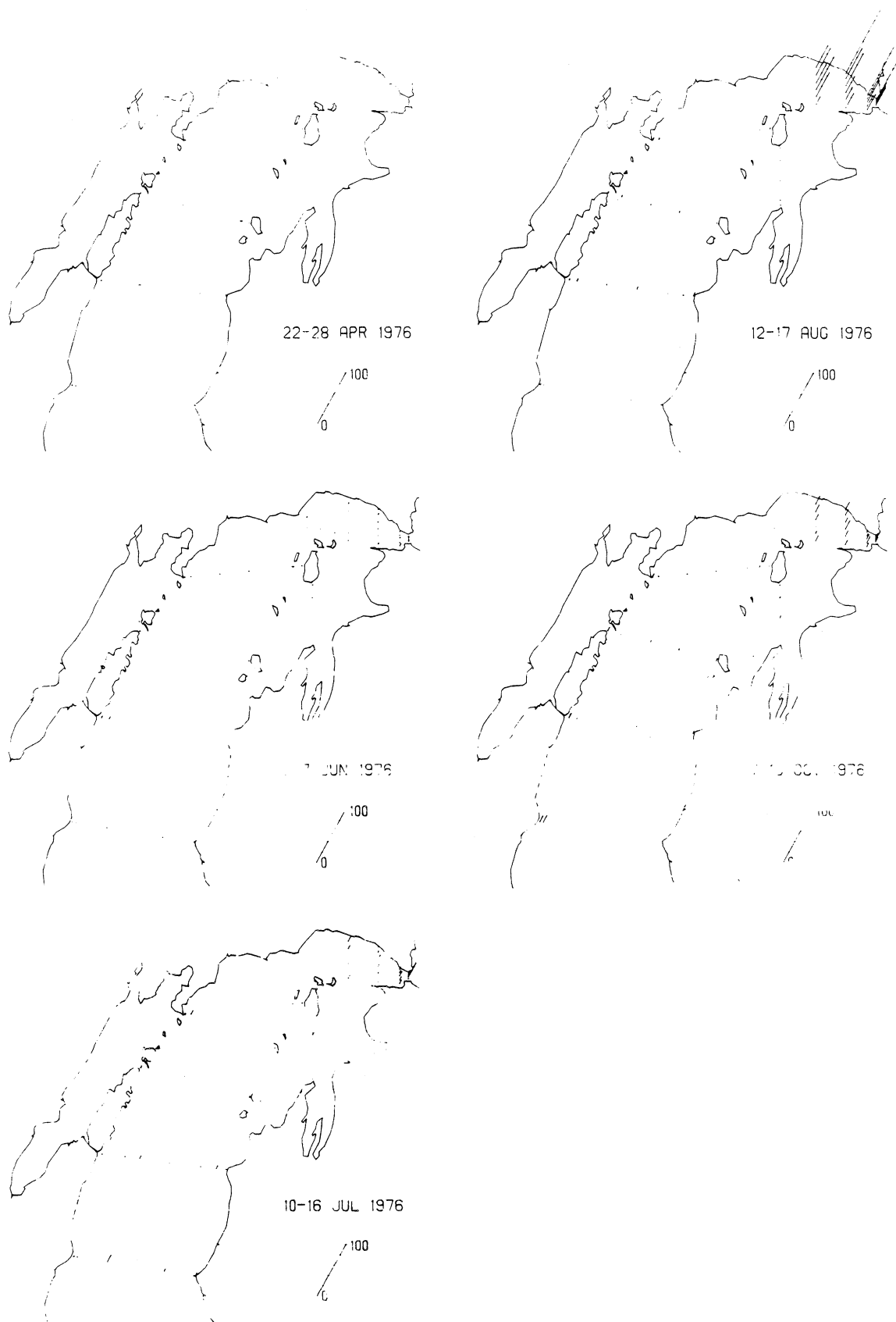


FIG. 48. Seasonal distribution of Cyclotella comta.

upwelling areas at Big Sable Point, Point Betsie, and south of Beaver Island, and in the Straits area. In October it was present at most stations in the Straits area, but only isolated occurrences were noted at the other stations sampled (Fig. 49).

Cyclotella pseudostelligera Hust., unlike members of the genus discussed above, is usually restricted to highly eutrophied areas. In northern Lake Michigan the only significant occurrences were at stations in the Rawley Point vicinity, near Manitowoc. Minor occurrences were noted at stations in the Big Sable Point vicinity, near Ludington, Michigan, and near the Sturgeon Bay Ship Canal (Fig. 50).

Cyclotella stelligera (Cl. & Grun.) V. H. is a major plankton dominant in the upper Great Lakes. It responds to phosphorus enrichment (Schelske and Stoermer 1972, Schelske et al. 1972), but is reduced in abundance in areas which are severely eutrophied (Stoermer 1978, Stoermer and Kreis 1980). In northern Lake Michigan (Fig. 51) it was present at most stations sampled in April and June and reached peak abundance during July. There was a tendency for abundance to be reduced at nearshore stations, particularly on the western side of the lake. Substantial populations of this species were found at stations in the Point Betsie vicinity during August but only isolated occurrences were noted at other stations sampled during the last two cruises.

Members of the genus Cymbella are primarily benthic. As might be expected, most occurrences noted in northern Lake Michigan (Fig. 52) came from nearshore stations or stations in the relatively shallow Straits area. Anomalously high numbers were found at Station 67, south of Beaver Island, during the July cruise.

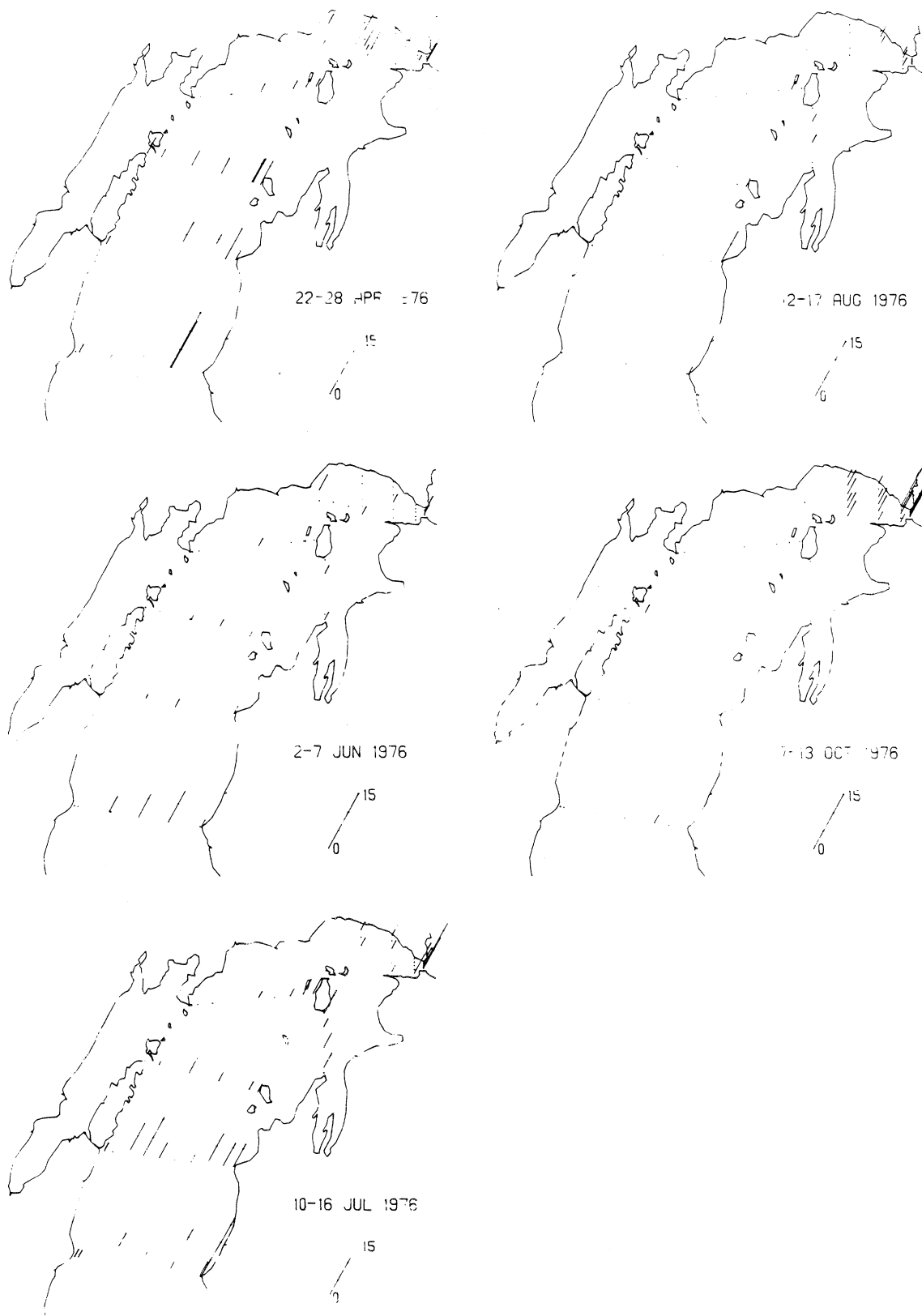


FIG. 49. Seasonal distribution of Cyclotella ocellata.



FIG. 50. Seasonal distribution of Cyclotella pseudostelligera.



FIG. 51. Seasonal distribution of Cyclotella stelligera.

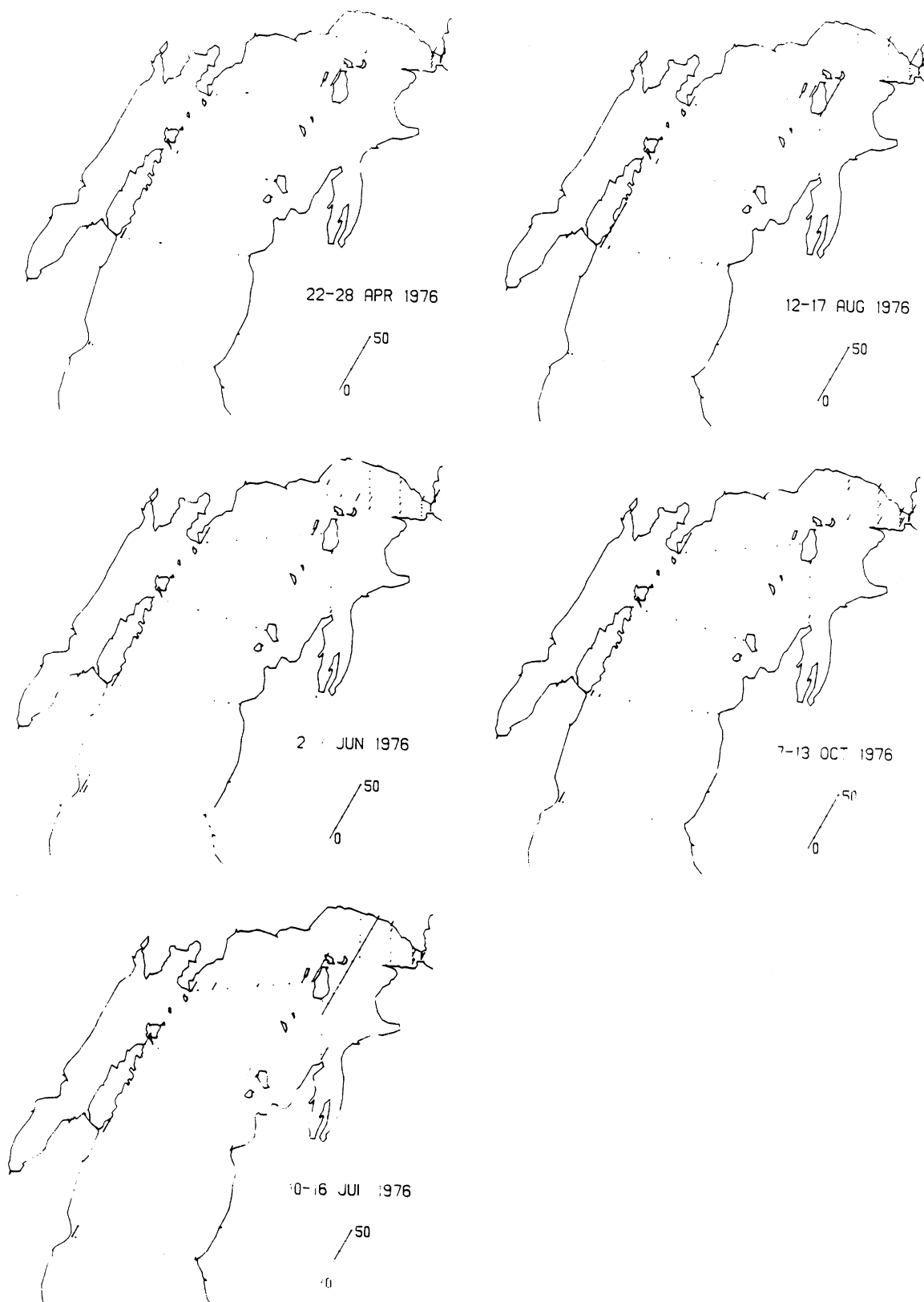


FIG. 52. Seasonal distribution of the genus Cymbella.

Diatoma tenue var. elongatum Lyngb. has been associated with ecological disturbance in the Great Lakes (Hohn 1969, Stoermer 1978). In northern Lake Michigan (Fig. 53), highest population levels occurred landward of the thermal bar in the spring. It became fairly widely distributed in the open waters in July, but these populations collapsed and only a few specimens were found in samples collected during the final two cruises.

Fragilaria crotonensis Kitt. is a widely distributed and apparently eurytopic taxon. It was widely distributed in northern Lake Michigan (Fig. 54) and abundance patterns were quite erratic. Highest abundance occurred in the Straits area during the early spring. Unlike many other species of diatoms, F. crotonensis maintained significant populations during summer stratification, particularly at nearshore stations, and recovered rapidly in the fall.

Fragilaria pinnata Ehr. is a primarily benthic species, however it is often entrained in the plankton and fairly large populations may be found in plankton samples from certain regions in the Great Lakes (e.g., Stoermer and Kreis 1980). Its distribution in northern Lake Michigan (Fig. 55) was unusual in that high abundance was restricted to nearshore stations on the western side of the lake. This occurrence pattern has previously been noted (Stoermer and Yang 1970), but the reason for it is not apparent.

Melosira islandica O. Müll. is a typical winter dominant in the Great Lakes. Because of its heavy silicification (Stoermer et al. 1981), it rapidly sinks out of the surface waters following stratification. Although intolerant of extremely eutrophic conditions, very high population densities are sometimes found at stations landward of the thermal bar during the spring (Stoermer and Kreis 1980). Its distribution in northern Lake Michigan

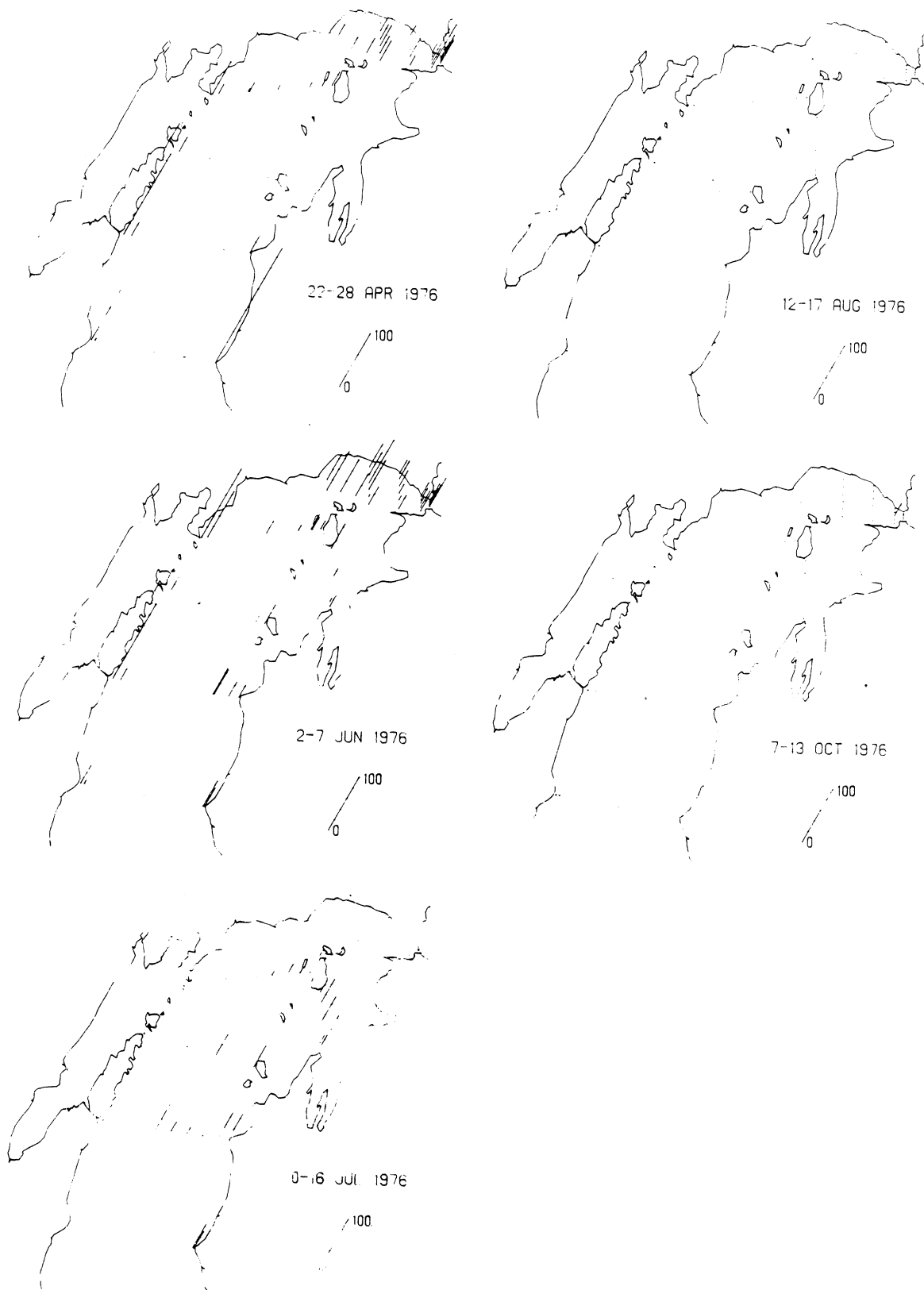


FIG. 53. Seasonal distribution of Diatoma tenue var. elongatum.



FIG. 54. Seasonal distribution of Fragilaria crotonensis.

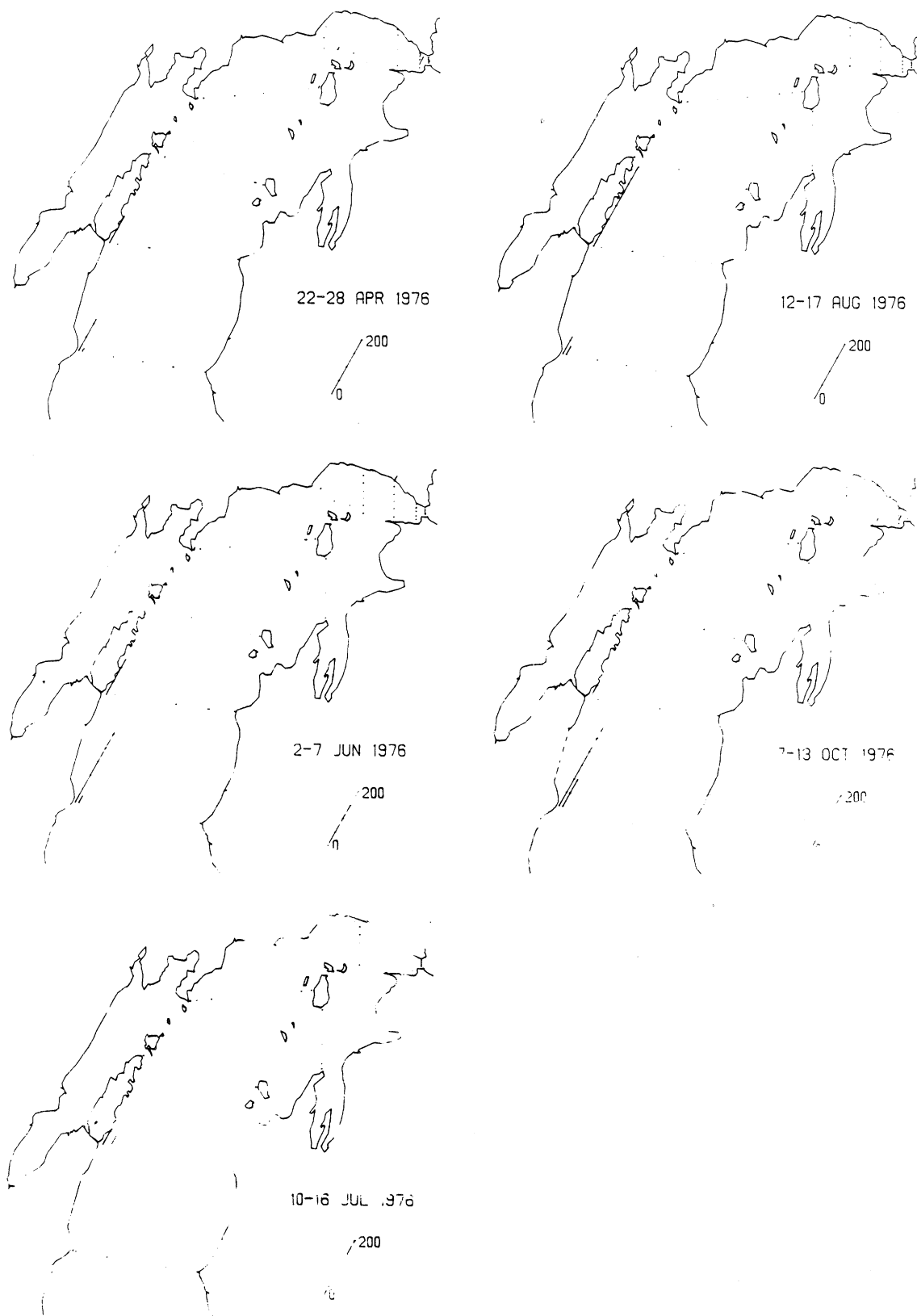


FIG. 55. Seasonal distribution of Fragilaria pinnata.

(Fig. 56) reflected these tendencies. Relatively high population densities were present at many stations sampled in April, particularly in the developing thermal bar region on the southern transect and at relatively shallow stations in the Straits region. With development of stratification, nearshore populations collapsed in June and offshore population densities were reduced to low levels by July and remained low during the rest of the sampling season.

Melosira italica subsp. subarctica O. Müll. The distribution and seasonal trends of population abundance of this species are quite similar to those of M. islandica (Stoermer 1978), although it has apparently become relatively more abundant in recent years than it was previously. Its distribution in the near-surface waters of northern Lake Michigan (Fig. 57) was similar to that of M. islandica, but population levels were even more depressed in the area affected by discharges from Green Bay, and populations of M. italica subsp. subarctica tended to persist longer into the summer stratified period.

Most members of the genus Navicula are primarily benthic. Like the benthic genera previously discussed, its distribution in near-surface plankton samples from northern Lake Michigan (Fig. 58) was largely restricted to nearshore stations. It also shows the same anomalously high abundance in the sample from Station 67 taken during the July cruise that was noted for Achnanthes and Cymbella.

Rhizosolenia eriensis H. L. Sm. was described originally from the Great Lakes and was widely distributed throughout the system. According to Hohn (1969) it has been nearly eliminated from Lake Erie and similar reductions in abundance have been noted in other eutrophied regions. In northern Lake Michigan (Fig. 59) largest populations were found in the Straits area during

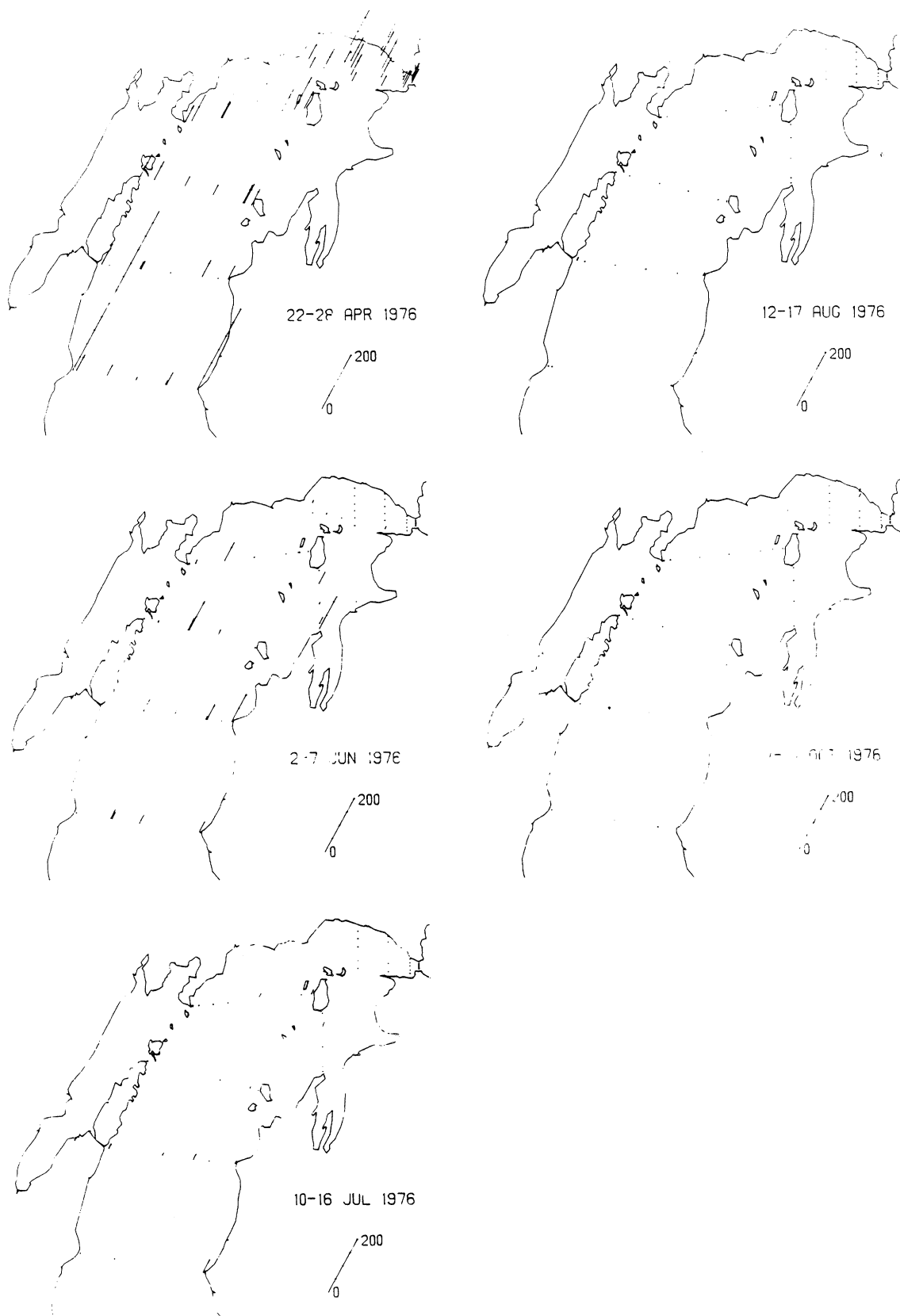


FIG. 56. Seasonal distribution of Melosira islandica.

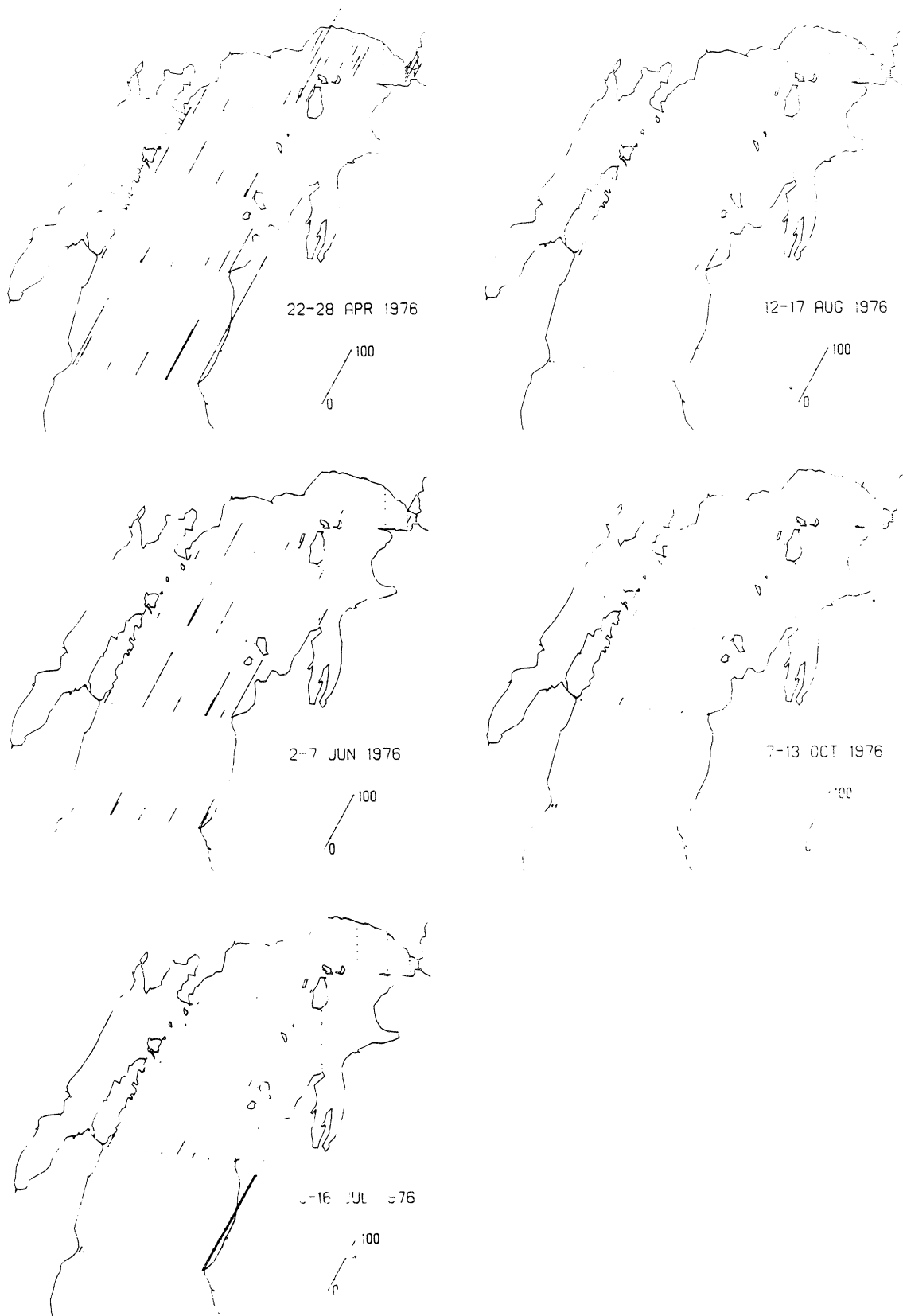


FIG. 57. Seasonal distribution of Melosira italica subsp. subarctica.

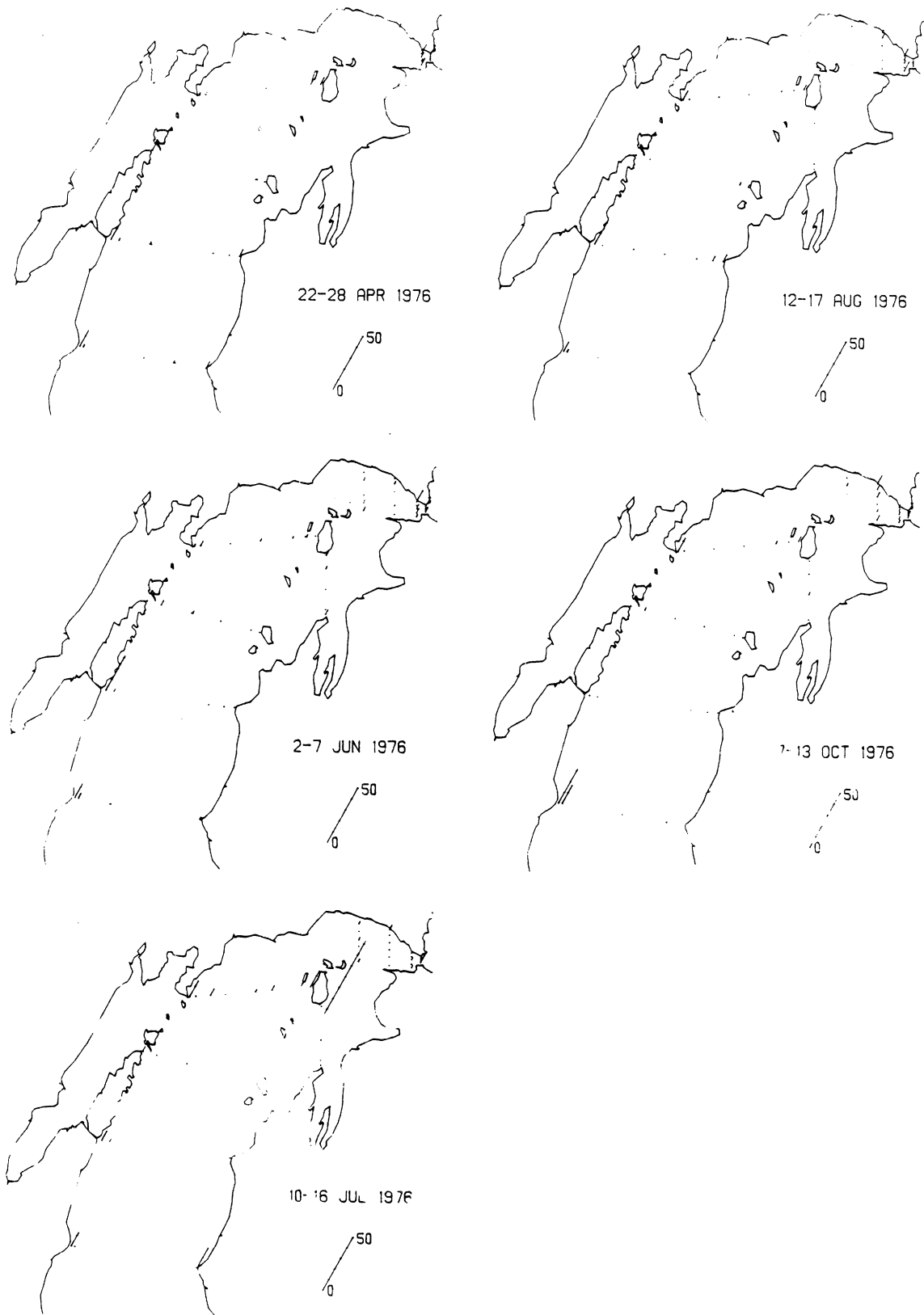


FIG. 58. Seasonal distribution of the genus Navicula.

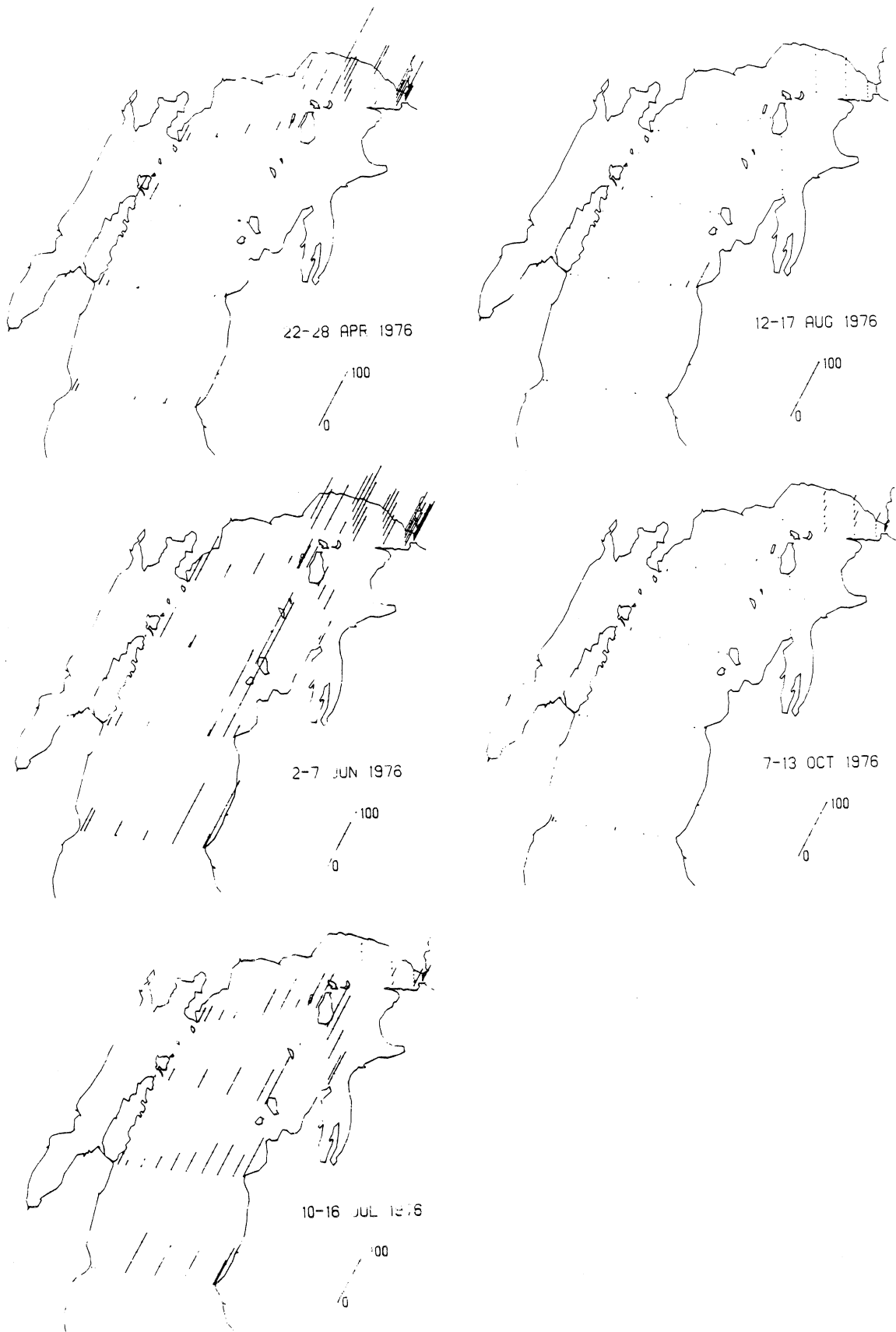


FIG. 59. Seasonal distribution of Rhizosolenia eriensis.

the April cruise. During June and July significant populations were found at most stations sampled and there was a trend toward highest abundance at stations on the eastern side of the lake. Populations of this species had collapsed by August and only a few occurrences were noted, especially in apparent upwelling areas. In October small populations were found in the Straits area and at occasional stations in the open lake.

Rhizosolenia gracilis H. L. Sm. was also originally described from the Great Lakes and has the same general ecological preferences as R. eriensis, although it is apparently somewhat more tolerant of eutrophication (Stoermer 1978). Its distribution in northern Lake Michigan was qualitatively similar to that of R. eriensis (Fig. 60) although it was less abundant and populations do not recover in the fall samples to the extent that R. eriensis does.

Stephanodiscus hantzschii Grun. is apparently widely distributed in mesotrophic to eutrophic lakes and often becomes a dominant population in small, highly eutrophic lakes. It is commonly reported from the Great Lakes, although there are substantial questions regarding the taxonomic interpretation in some reports. In the Great Lakes it appears to be most abundant during the winter and early spring, when nutrients are abundant, and to maintain high population levels into the stratified period only in areas which are severely eutrophied (Stoermer et al. 1974). In northern Lake Michigan it was relatively abundant at stations sampled during the April cruise, became less abundant in June, and was virtually absent during the rest of the year (Fig. 61).

Stephanodiscus minutus Grun. is somewhat similar to S. hantzschii in occurrence and distribution, but tends to be less characteristic of highly eutrophic environments. In northern Lake Michigan it was abundant at stations



FIG. 60. Seasonal distribution of Rhizosolenia gracilis.

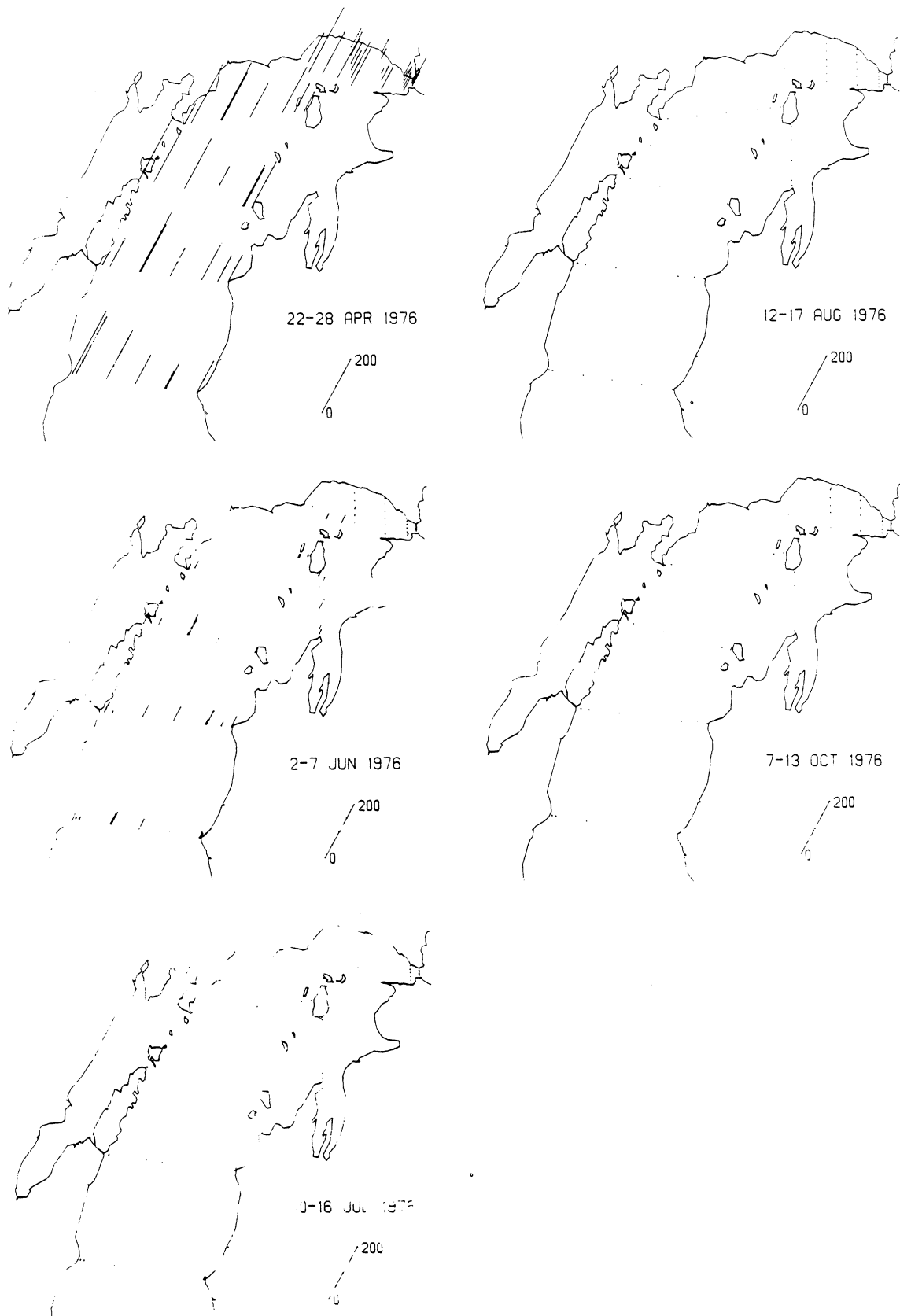


FIG. 61. Seasonal distribution of Stephanodiscus hantzschii.

sampled during the April and June cruises (Fig. 62) and isolated populations were noted during the other cruises, particularly at stations on the eastern side of the lake. In October it was uniformly present, although in low abundance at stations in the Straits area.

Stephanodiscus subtilis (Van Goor) A. Cl. is characteristic of extremely eutrophied and disturbed regions of the Great Lakes. It is often a dominant population in polluted rivers entering the lakes, and very high population densities are found in areas such as Saginaw Bay. In northern Lake Michigan its occurrence in near-surface samples was restricted to Station 2 off Rawley Point near Manitowoc, Wisconsin (Fig. 63). It is reported as occasionally abundant in Green Bay (Stoermer and Stevenson 1980) but these populations apparently do not survive transport into open Lake Michigan.

Synedra filiformis Grun. is a common and widely distributed form in the upper Great Lakes. It apparently is able to utilize relatively low levels of nutrients. In northern Lake Michigan its distribution and abundance patterns tended to follow the very general pattern of temperature change and nutrient depletion in the surface waters (Fig. 64). It was relatively abundant at stations in the Straits region and at nearshore stations during April and June. Maximum abundance in the offshore waters occurred in July, only to collapse by August. Small populations were again present by October, particularly in the Straits region.

Synedra delicatissima var. angustissima Grun. is morphologically similar to S. filiformis and has somewhat similar ecological affinities. In northern Lake Michigan (Fig. 65) it was most abundant in the far northern part of the lake early in the season. Population levels were much reduced by July, and no

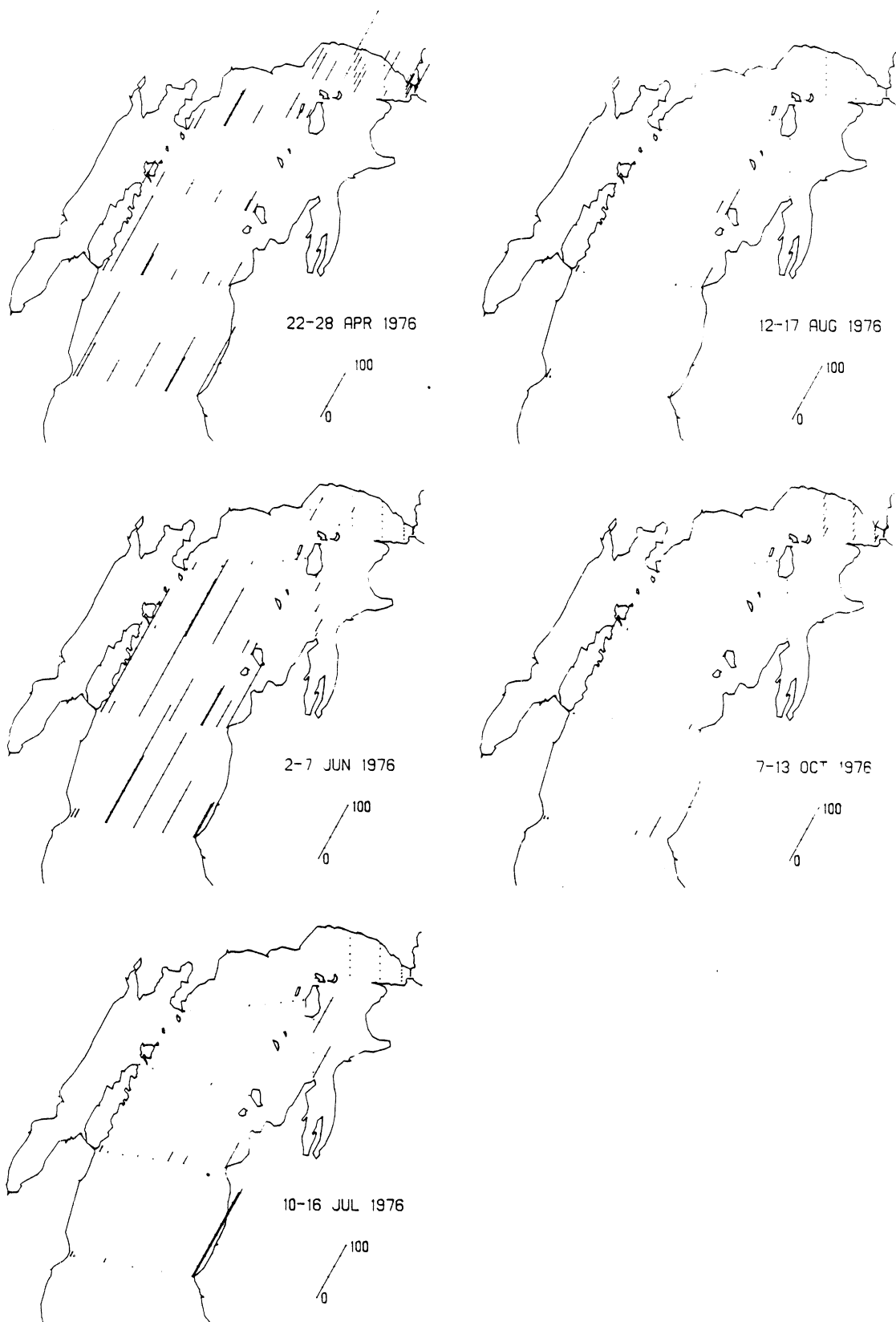


FIG. 62. Seasonal distribution of Stephanodiscus minutus.



FIG. 63. Seasonal distribution of Stephanodiscus subtilis.

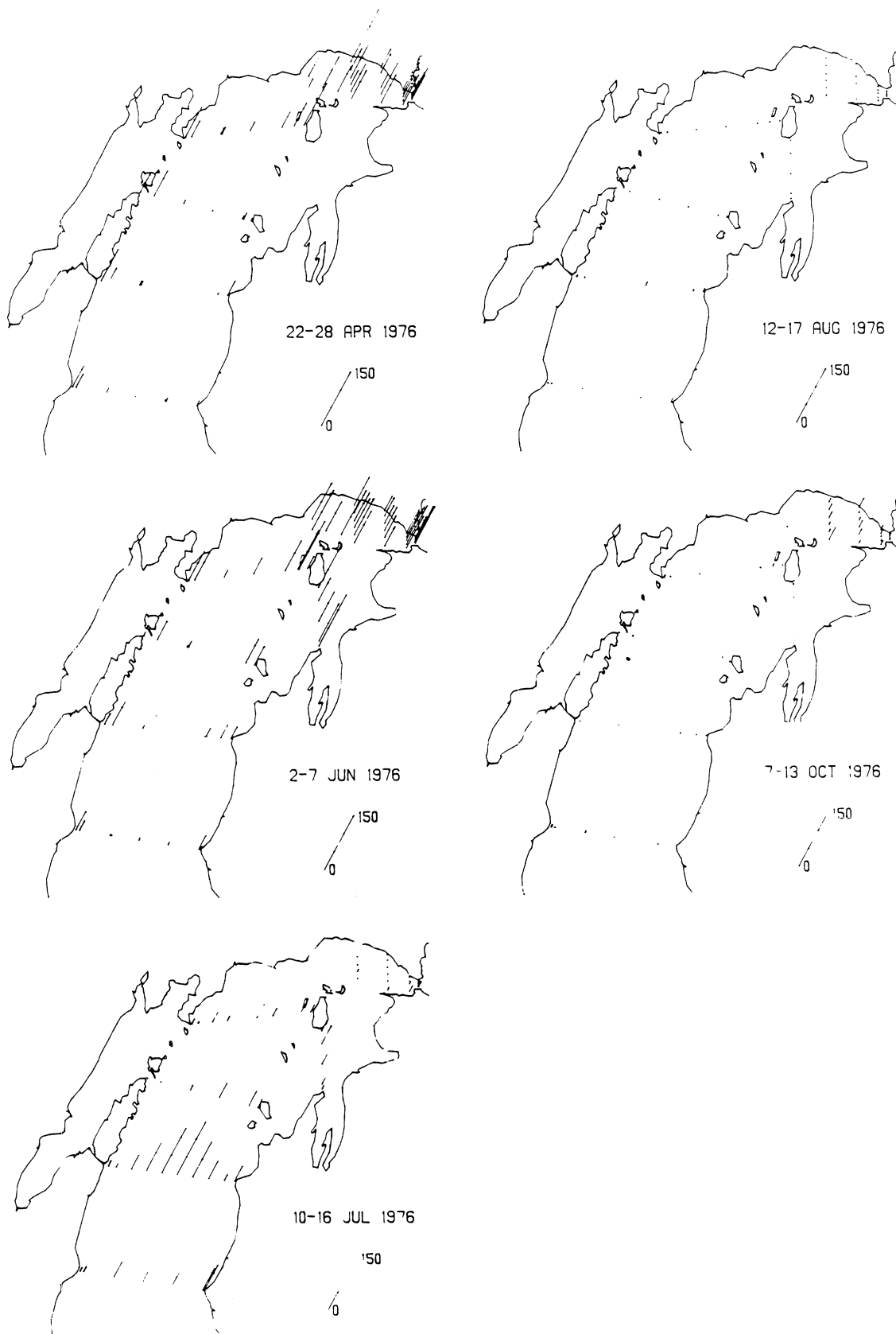


FIG. 64. Seasonal distribution of Synedra filiformis.

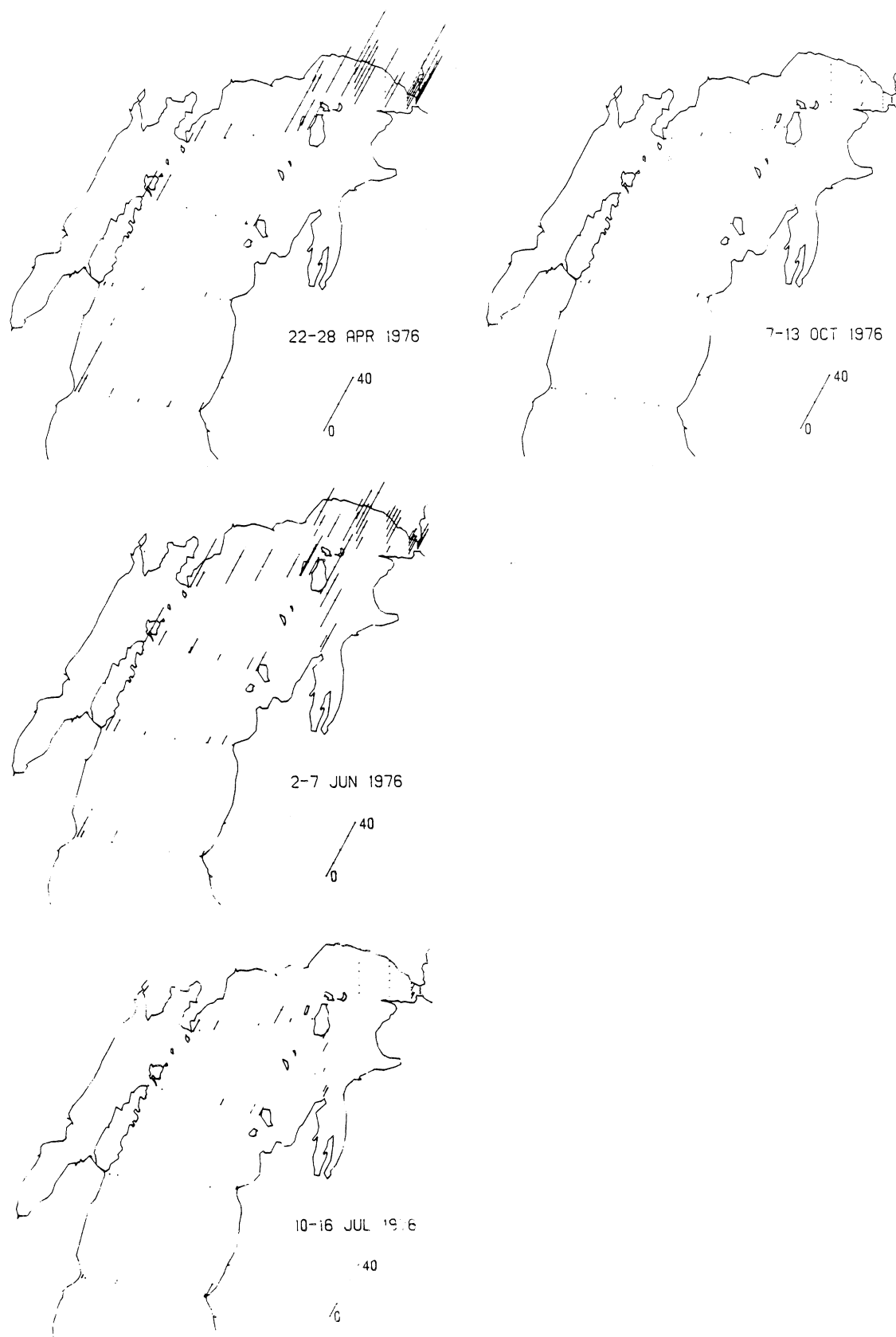


FIG. 65. Seasonal distribution of *Synedra delicatissima* var. *angustissima*.

specimens were found in the August near-surface samples. It was noted again in scattered samples from the October cruise, but in very low abundance.

Synedra ostenfeldii (Krieger) A. Cl. is a colonial species characteristic of mesotrophic to eutrophic large lakes. It was not particularly abundant in northern Lake Michigan (Fig. 66), but populations were noted at a number of stations early in the year. It occurred at stations in the Straits area and stations landward of the thermal bar in April and June. By July these populations had largely disappeared, but S. ostenfeldii was present in maximum yearly abundance at offshore stations on the southern two transects.

Tabellaria flocculosa var. linearis Koppen is a representative of a genus widely reported as a major plankton dominant in the Great Lakes system. The distribution of this entity in northern lake Michigan (Fig. 67) was somewhat unusual. In April it was abundant at stations in the Straits area and, especially, at nearshore stations along the western coast. Highest abundance occurred at Station 29 near Death's Door. A similar pattern was observed in June, although abundance at stations in the Straits area declined relative to stations near Green Bay. Populations were more widely distributed, but reduced in numbers by July, and only a few occurrences were noted in August. Population densities increased again in October, particularly at stations where this entity had been abundant during the spring.

The Chlorophyta (green algae - Fig. 68) was a more important component of phytoplankton assemblages in northern Lake Michigan than might be supposed on the basis of historic reports. Scattered populations were noted during the April and June cruises and green algae were present in relatively high abundance at all stations after stratification. Highest abundance was found during the August cruise, particularly at stations in the Straits area. The

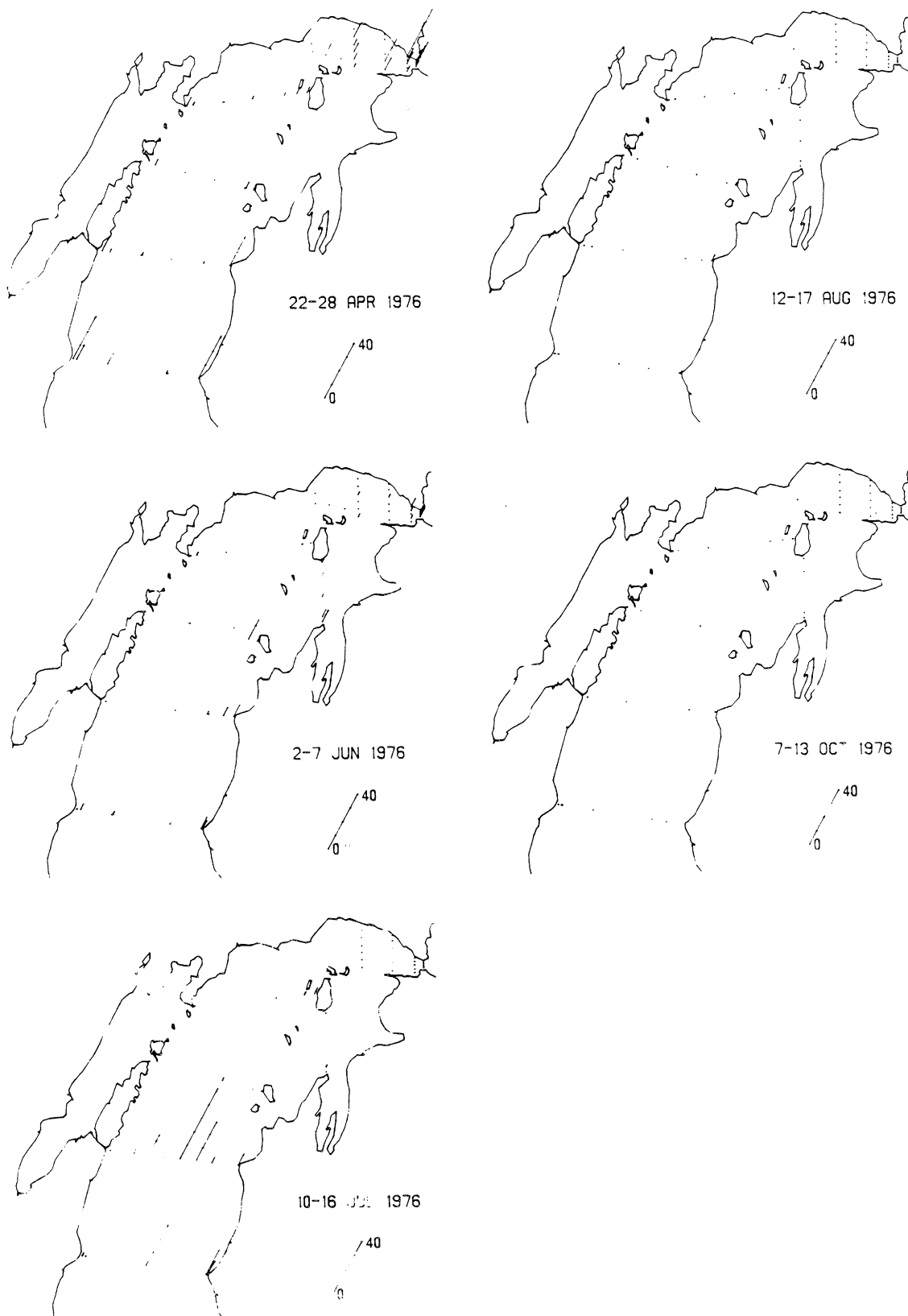


FIG. 66. Seasonal distribution of Synedra ostenfeldii.

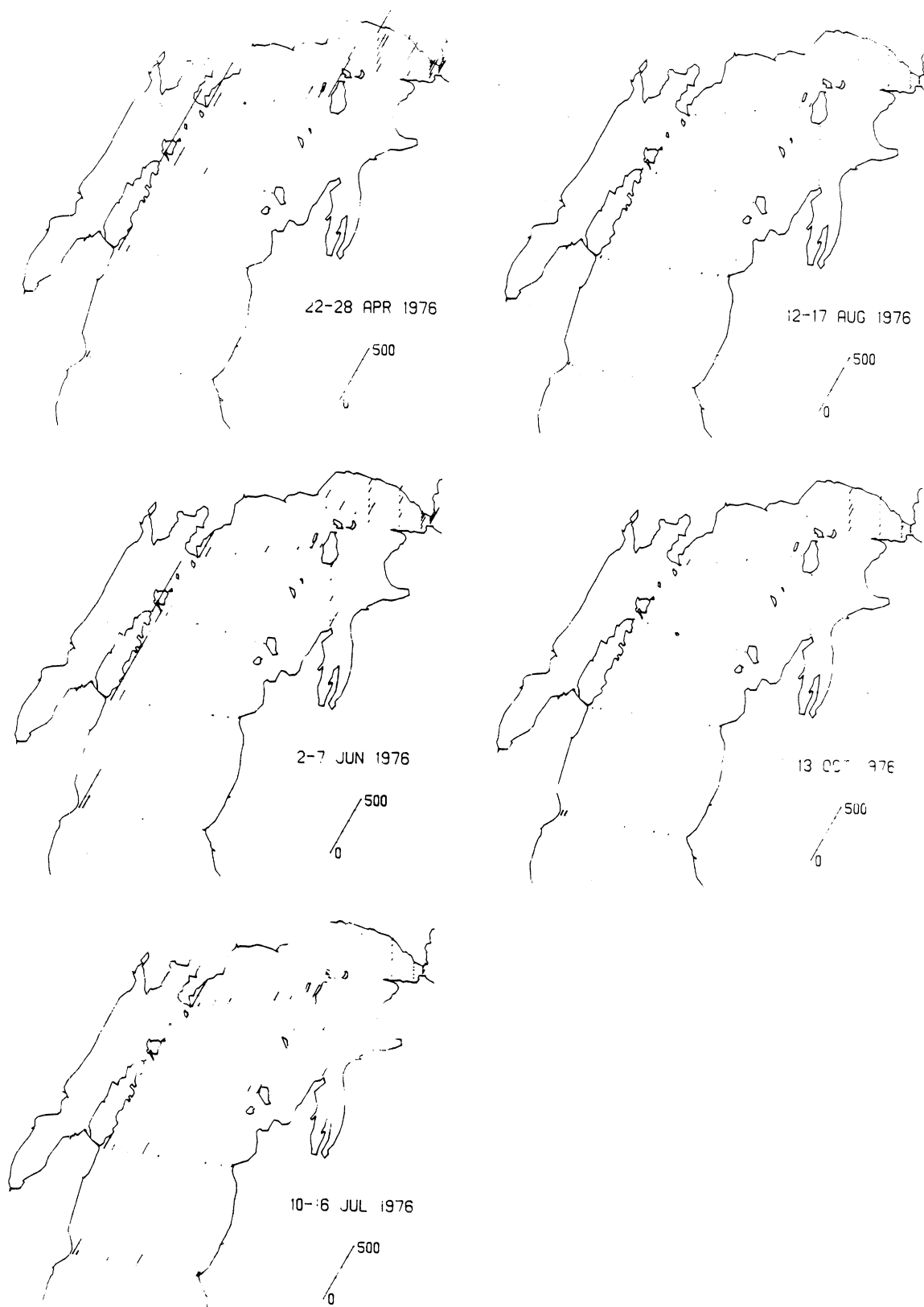


FIG. 67. Seasonal distribution of Tabellaria flocculosa var. linearis.

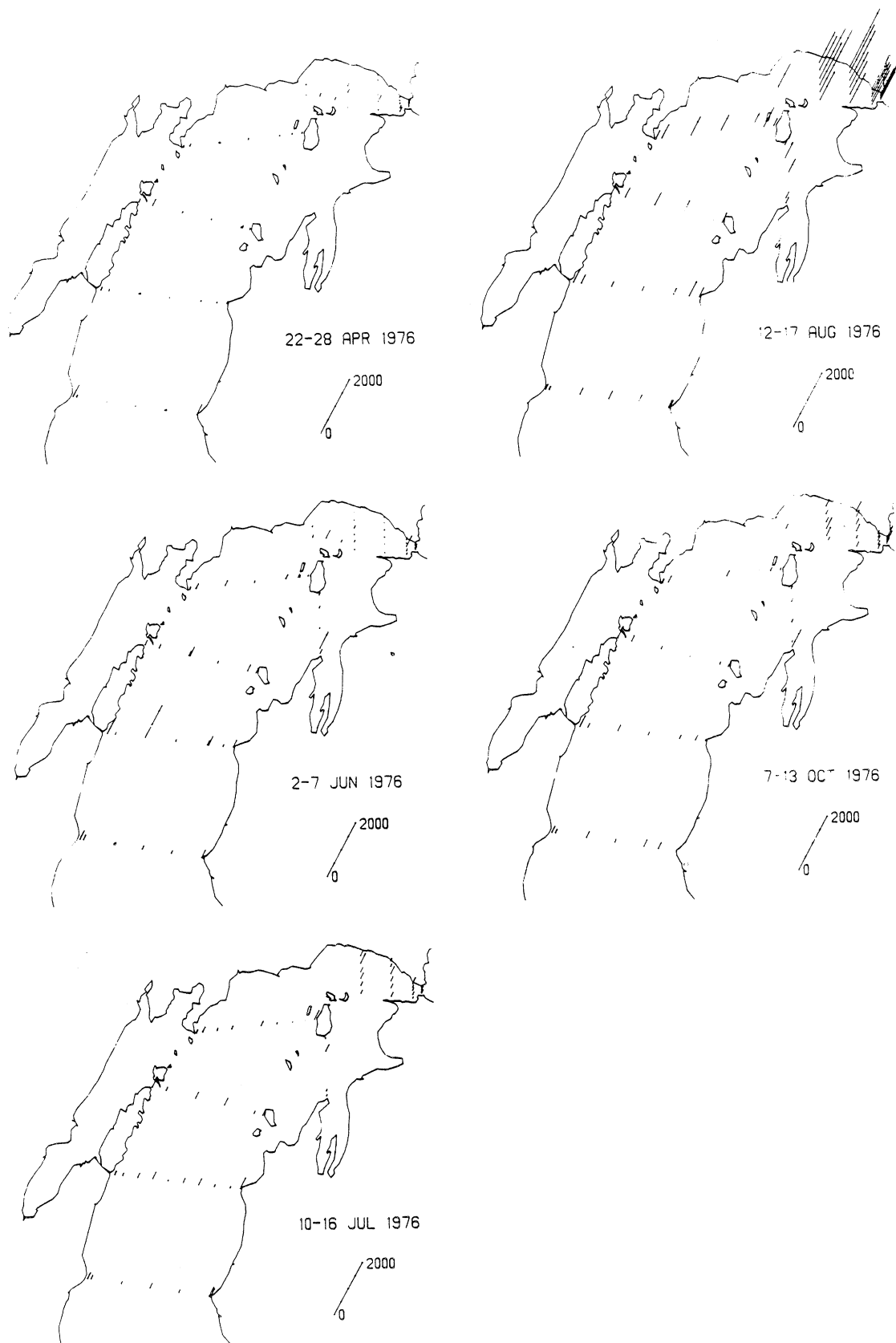


FIG. 68. Seasonal distribution and abundance trends of green algae.

increased abundance following stratification might be expected on the basis of Schelske and Stoermer's (1971) projection of the effects of silica depletion in Lake Michigan, but it should be emphasized that the overall increase is also related to the abundance of certain taxa in the spring, which have not previously been reported from Lake Michigan.

Ankistrodesmus falcatus (Corda) Ralfs has been reported as being abundant in early spring samples from Lake Ontario (Stoermer et al. 1974). In northern Lake Michigan it was relatively abundant and uniformly distributed in April and June samples (Fig. 69). Following stratification, population levels declined and this species was a minor component of phytoplankton assemblages for the rest of the season.

An unidentified member of the genus Ankistrodesmus (sp. #6) had quite different behavior in northern Lake Michigan (Fig. 70). It was not noted in our April and June samples, but occurred in relatively high abundance at most stations sampled in July. Populations declined at open lake stations by August but high population densities were maintained in the Straits area. This species had declined further to very low abundance by October.

Although present earlier in the year, Gloeocystis planctonica (West and West) Lemm. had a similar pattern of seasonal distribution (Fig. 71). This species is common in Lake Huron (Stoermer and Kreis 1980) and Lake Ontario (Stoermer et al. 1974) and is apparently becoming more abundant in Lake Michigan. It did not appear to be particularly associated with high levels of eutrophication, but was probably favored by silica depletion during summer stratification.

Nephrocytium agardhianum Näg. is an example of a green alga which had much more limited seasonal distribution in northern Lake Michigan (Fig. 72).

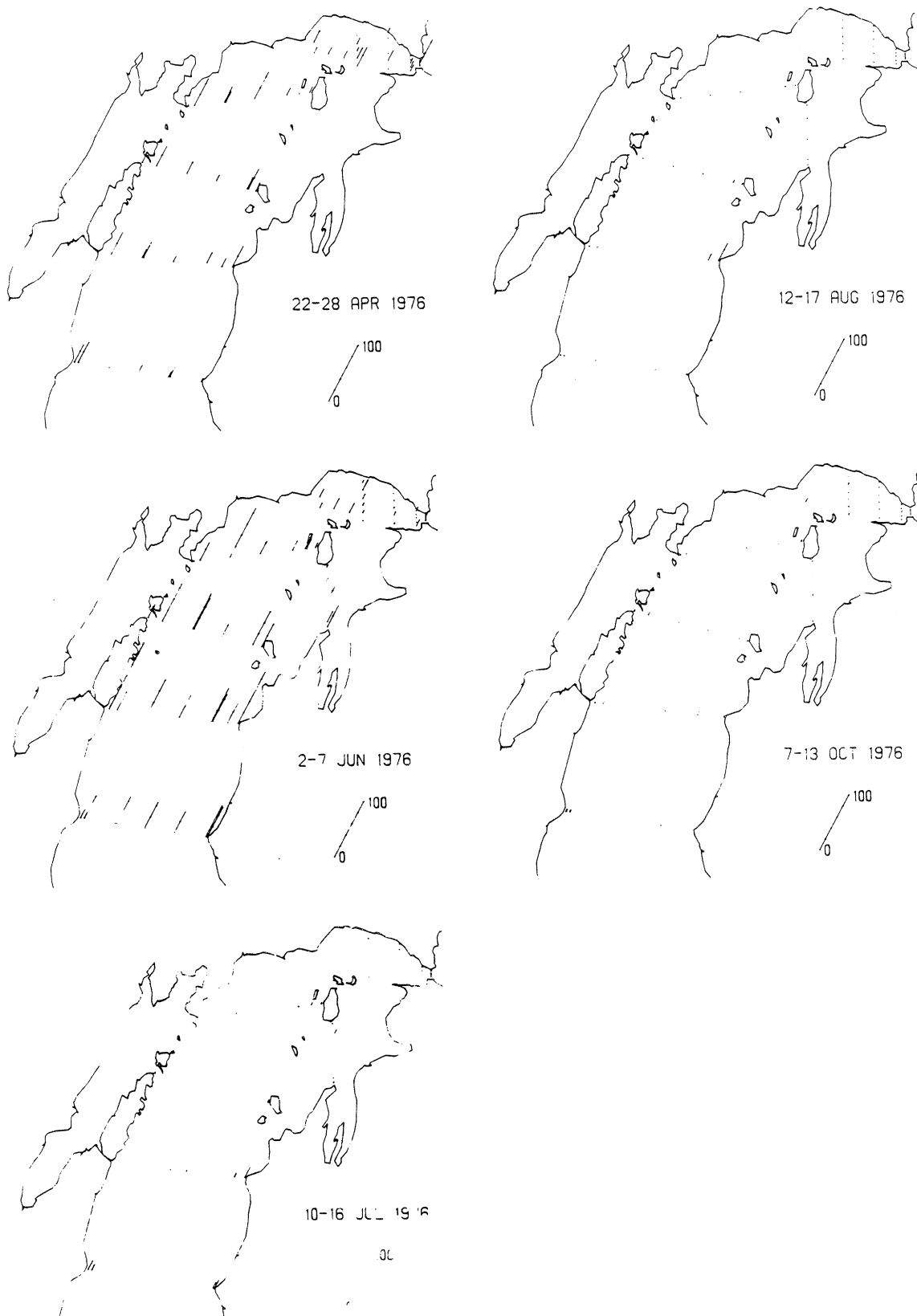


FIG. 69. Seasonal distribution of Ankistrodesmus falcatus.

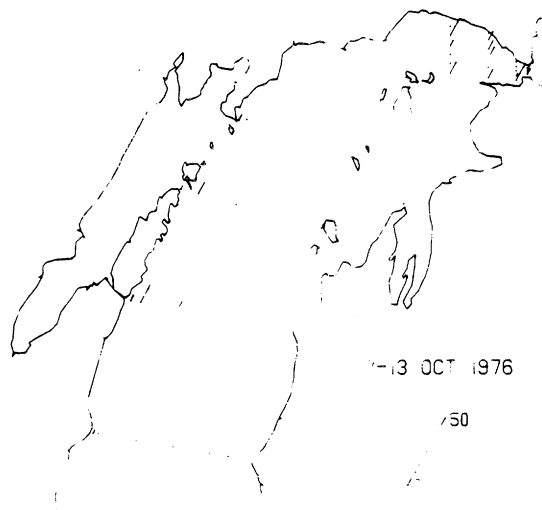
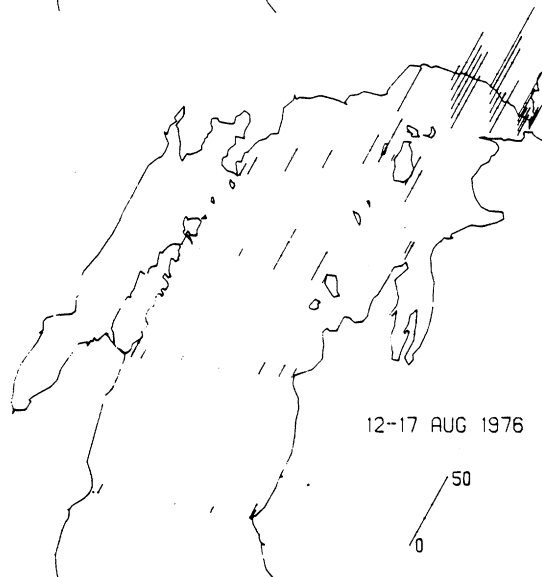
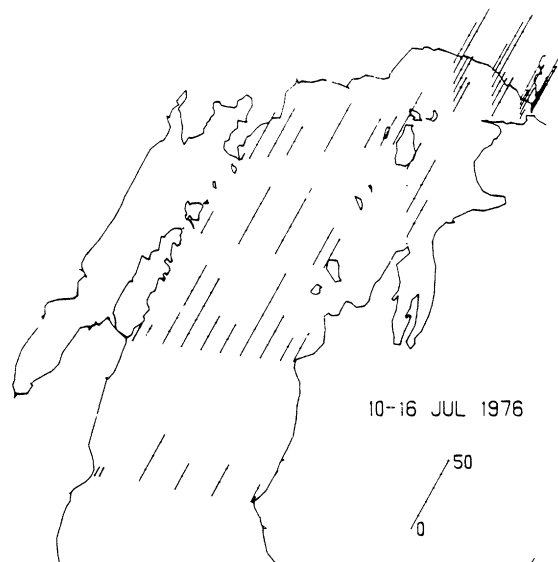


FIG. 70. Seasonal distribution of Ankistrodesmus (sp. #6).

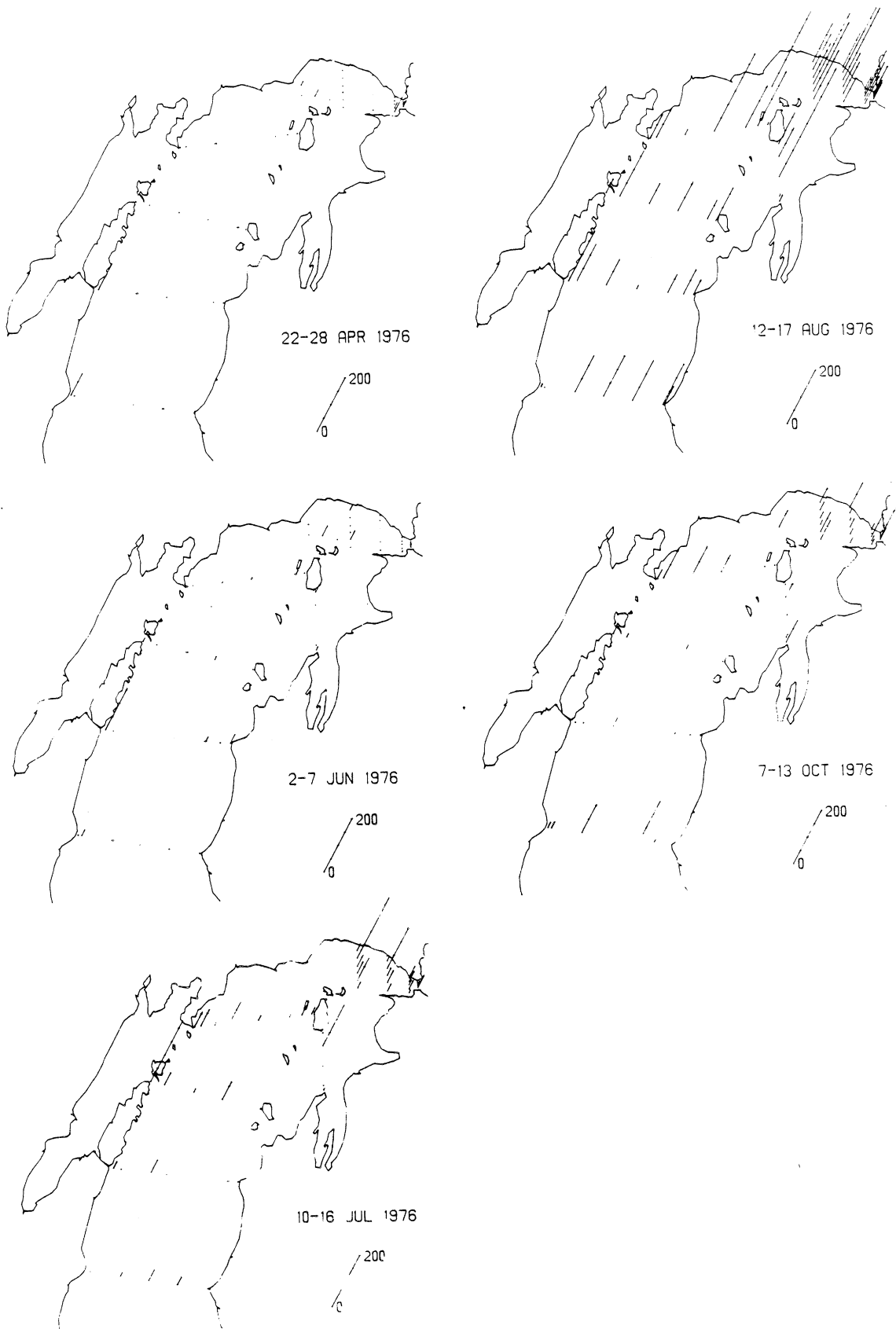


FIG. 71. Seasonal distribution of Gloeocystis planctonica.

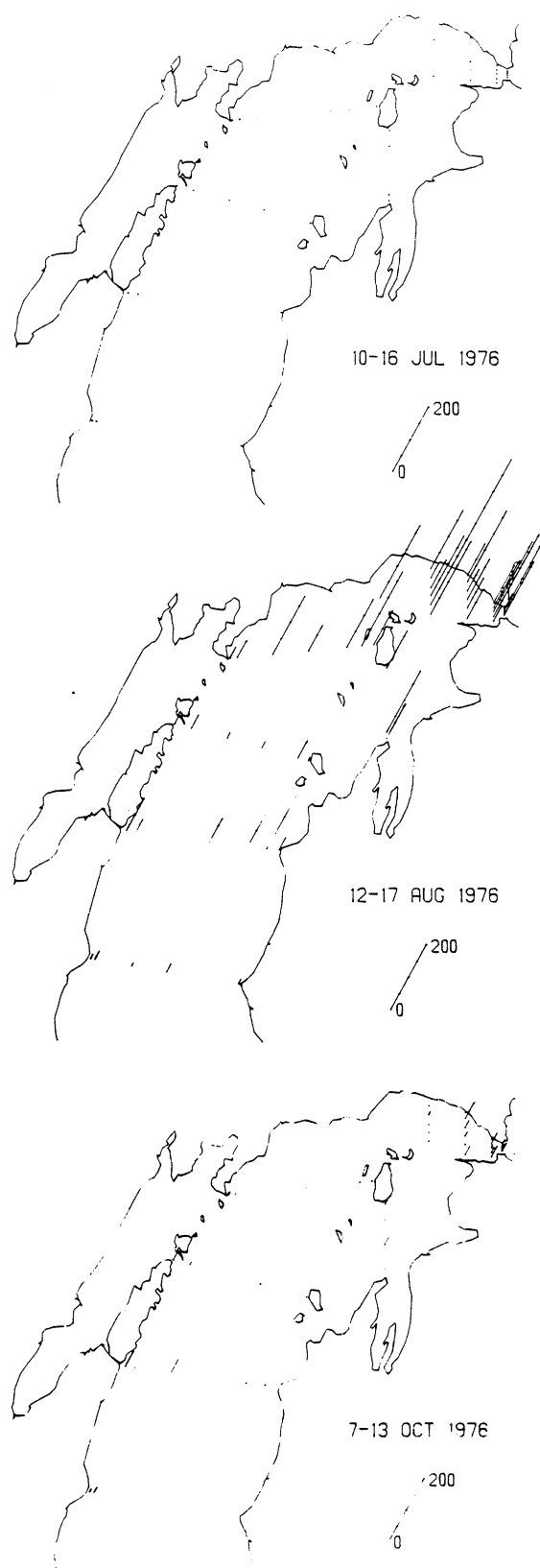


FIG. 72. Seasonal distribution of Nephrocystium agardhianum.

It was present in very low quantities in July, became a major component of phytoplankton assemblages in the near-surface waters by August, then declined to insignificant levels by October. This species has not been reported in large quantities in most investigations of phytoplankton in the Great Lakes.

Scenedesmus bicellularis Chod., on the other hand, is usually associated with highly eutrophied regions of the Great Lakes. Stoermer et al. (1974) report it as a spring dominant in Lake Ontario and Vollenweider et al. (1974) list it [as S. bijuga var. irregularis G. M. Sm. - see Uherkovich (1966) for discussion of systematics of this genus] as a characteristic species in Lake Ontario and Lake Erie, although no abundance estimates are provided. In northern Lake Michigan it was abundant at most stations sampled in the spring, reaching maximum abundance in June (Fig. 73). Only isolated populations were noted in subsequent samples, although it remained abundant at Stations 2 and 10 in July.

Many members of the Chrysophyta are motile cells which are capable of rapid response to changing nutrient conditions and may form transient blooms. This behavior was reflected in the general distribution of the group in northern Lake Michigan (Fig. 74). Chrysophytes were most abundant in the Straits area and at stations landward of the thermal bar in April and June, reaching their greatest abundance in June. Following the establishment of stratification, populations declined in the nearshore waters, but the group remained relatively abundant at offshore stations sampled in July.

Members of the genus Dinobryon have historically been considered an important component of phytoplankton assemblages in Lake Michigan (Ahlstrom 1936). Because they form large colonies they tend to be oversampled in net collections, and even with other sampling techniques their abundance tends to

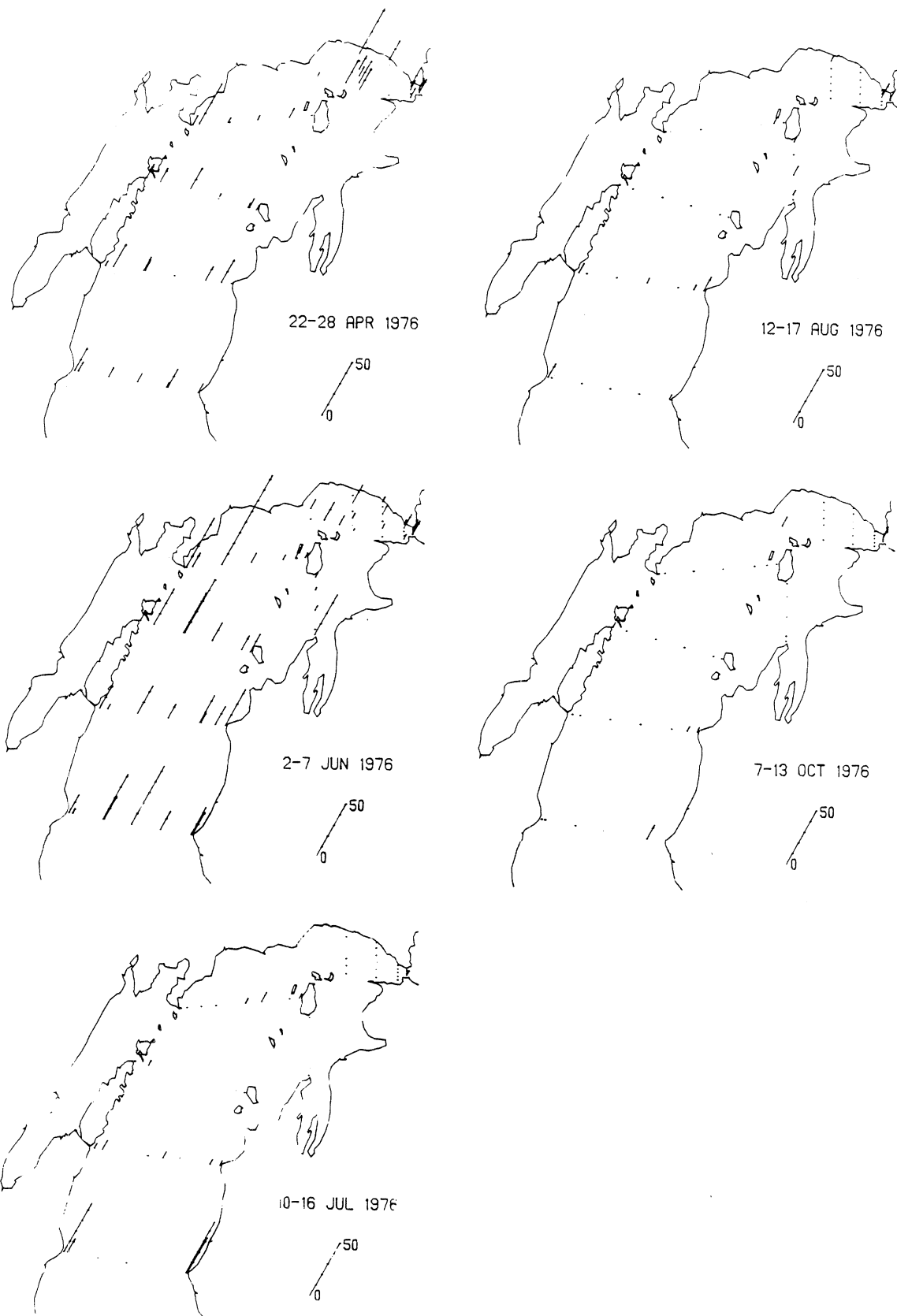


FIG. 73. Seasonal distribution of Scenedesmus bicellularis.

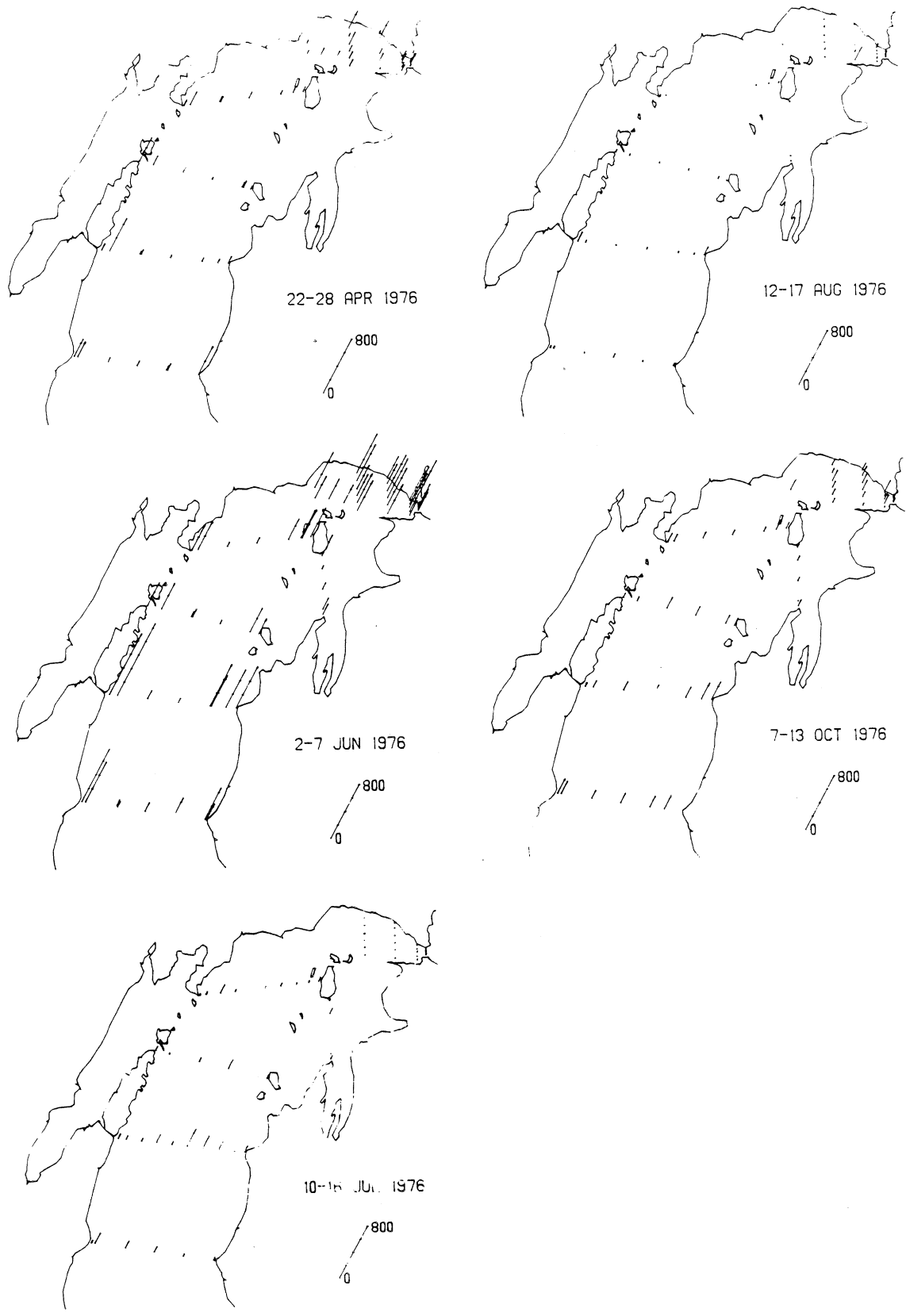


FIG. 74. Seasonal distribution and abundance of chrysophytes.

be patchy and population estimates have large uncertainties. Numerous authors (e.g., Hutchinson 1967) have commented on the tendency of members of this genus to occur in abundance following blooms of other taxa. Distribution of Dinobryon in northern Lake Michigan is an example of this pattern. Maximum population abundance first developed at shallow stations in the Straits area and followed the excursion of the thermal bar in the open lake. Population densities were minimal in August, but redeveloped at stations in the Straits area and along the Michigan coast by October (Fig. 75).

Our samples from Northern Lake Michigan contained significant numbers of small species of Ochromonas of uncertain specific affinities. The general distribution of these entities (Fig. 76) was somewhat similar to Dinobryon but populations tended to be more evenly distributed, both seasonally and areally, and regenerated more rapidly in the fall.

The Cyanophyta (blue-green algae) were an important component of phytoplankton assemblages in northern Lake Michigan, particularly in the fall (Fig. 77). Relatively small populations were present in spring and early summer samples. High population levels were noted in August, particularly at stations near Green Bay, and the blue-green algae became an important component of phytoplankton assemblages sampled by October.

The distribution of Anabaena flos-aquae (Lyngb.) Bréb., a potential nuisance form, was highly irregular. Large populations were noted at isolated stations sampled in July and August, but no particular distribution pattern was evident (Fig. 78).

Anacystis incerta (Lemm.) Dr. & Daily was much more generally distributed in our samples (Fig. 79). This species is a potential nuisance population which has become quite abundant in disturbed regions of the Great Lakes. In



FIG. 75. Seasonal distribution of the genus Dinobryon.

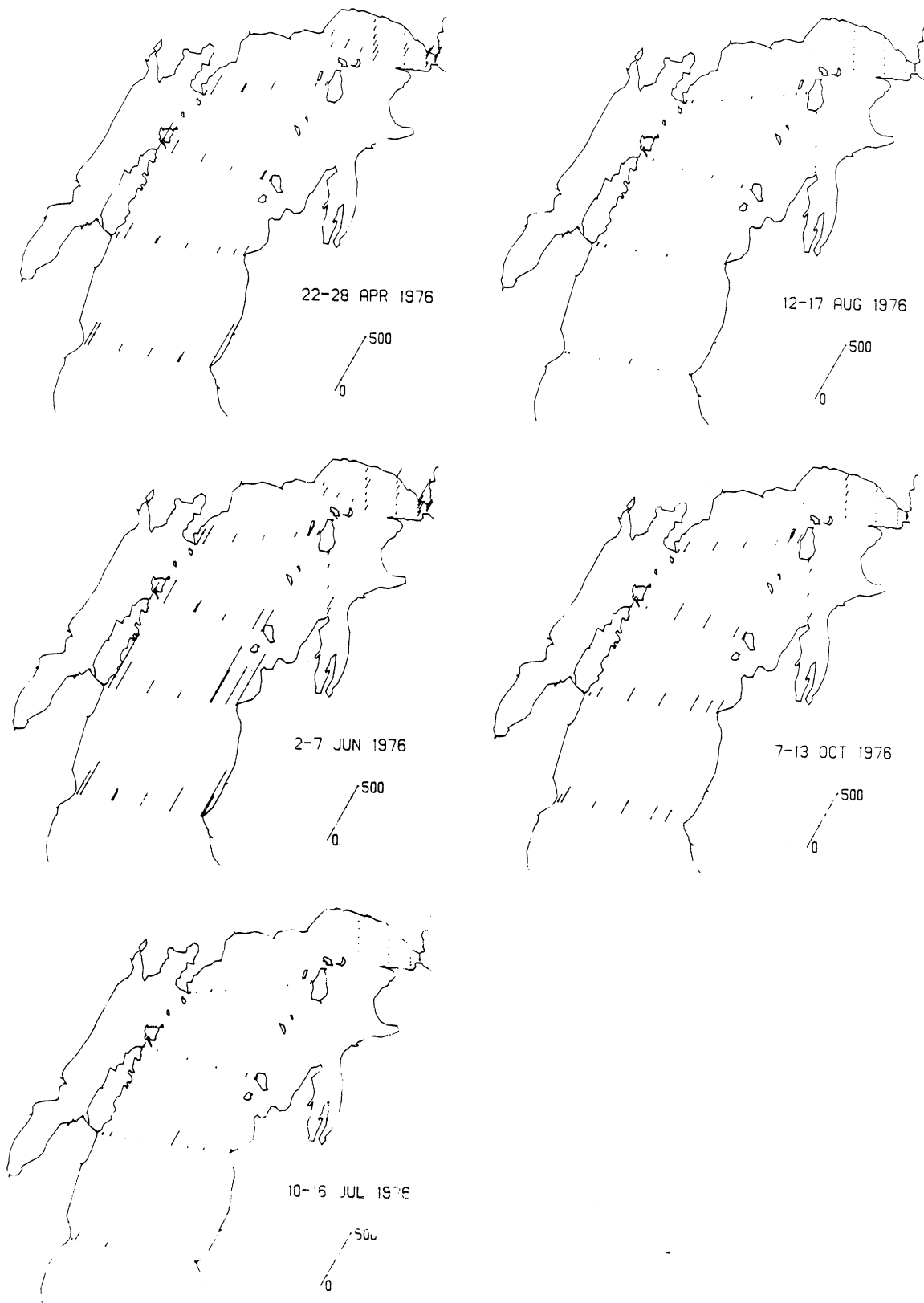


FIG. 76. Seasonal distribution of the genus Ochromonas.

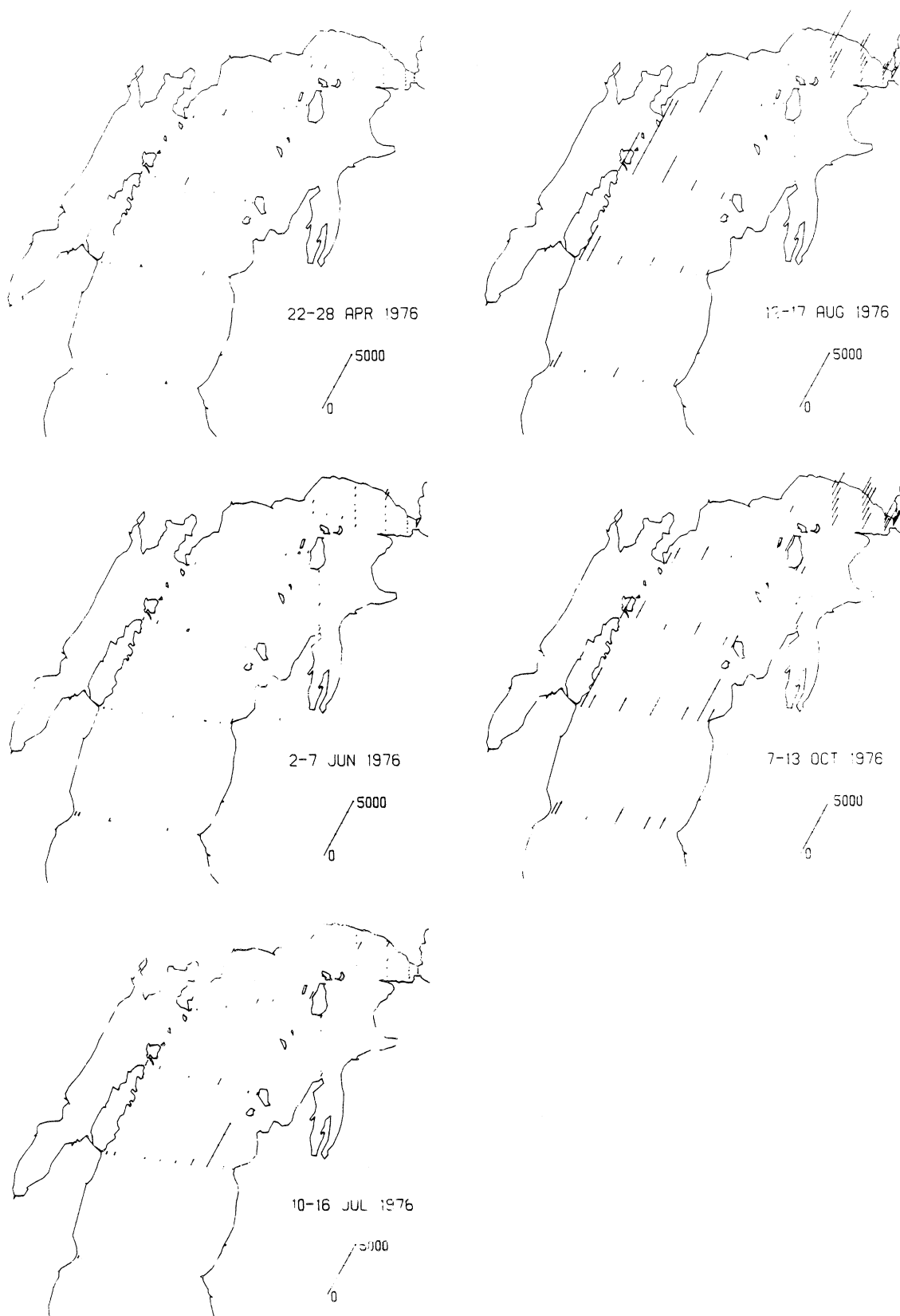


FIG. 77. Seasonal distribution and abundance of blue-green algae (cells/mL).

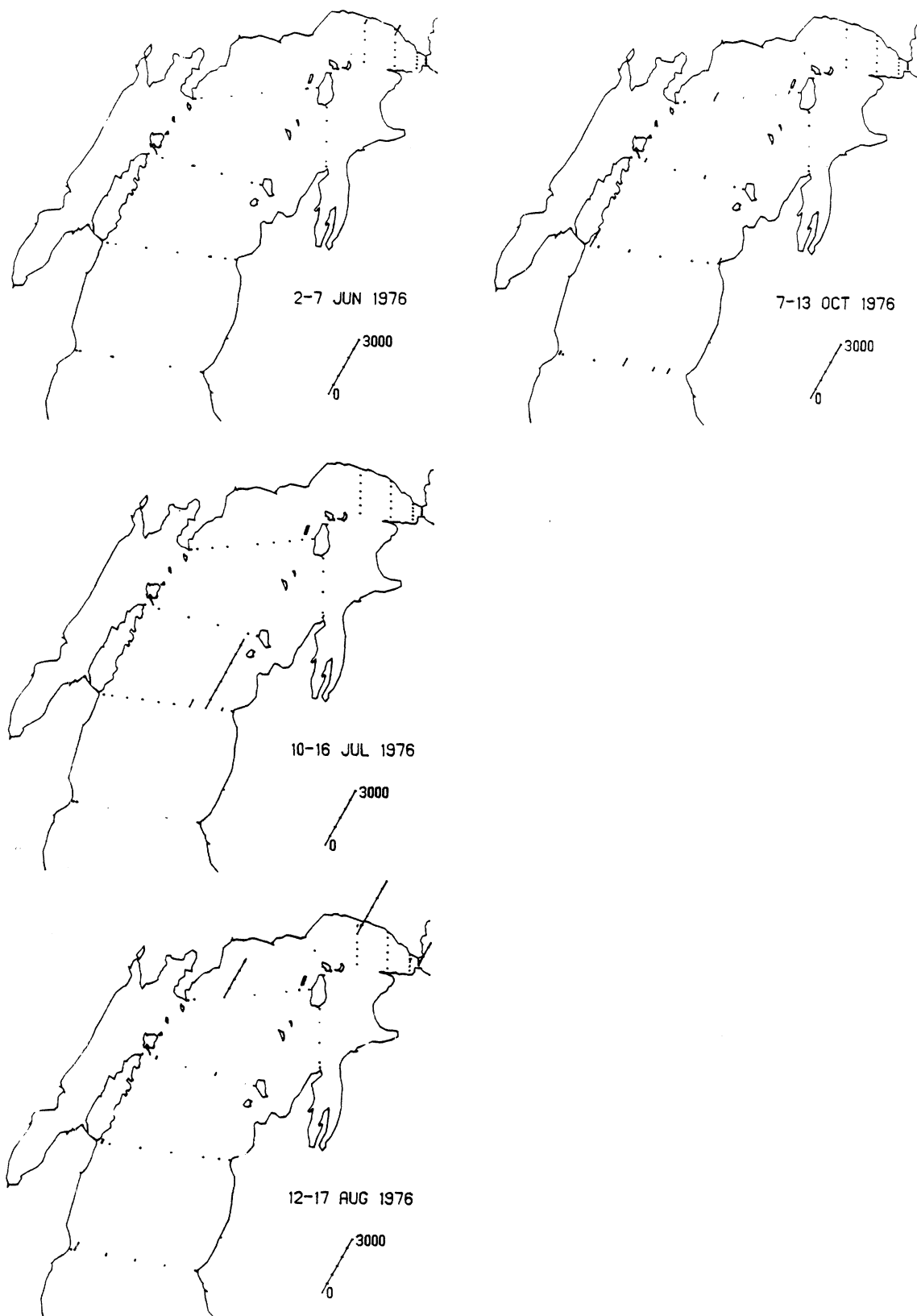


FIG. 78. Seasonal distribution of *Anabaena flos-aquae*.

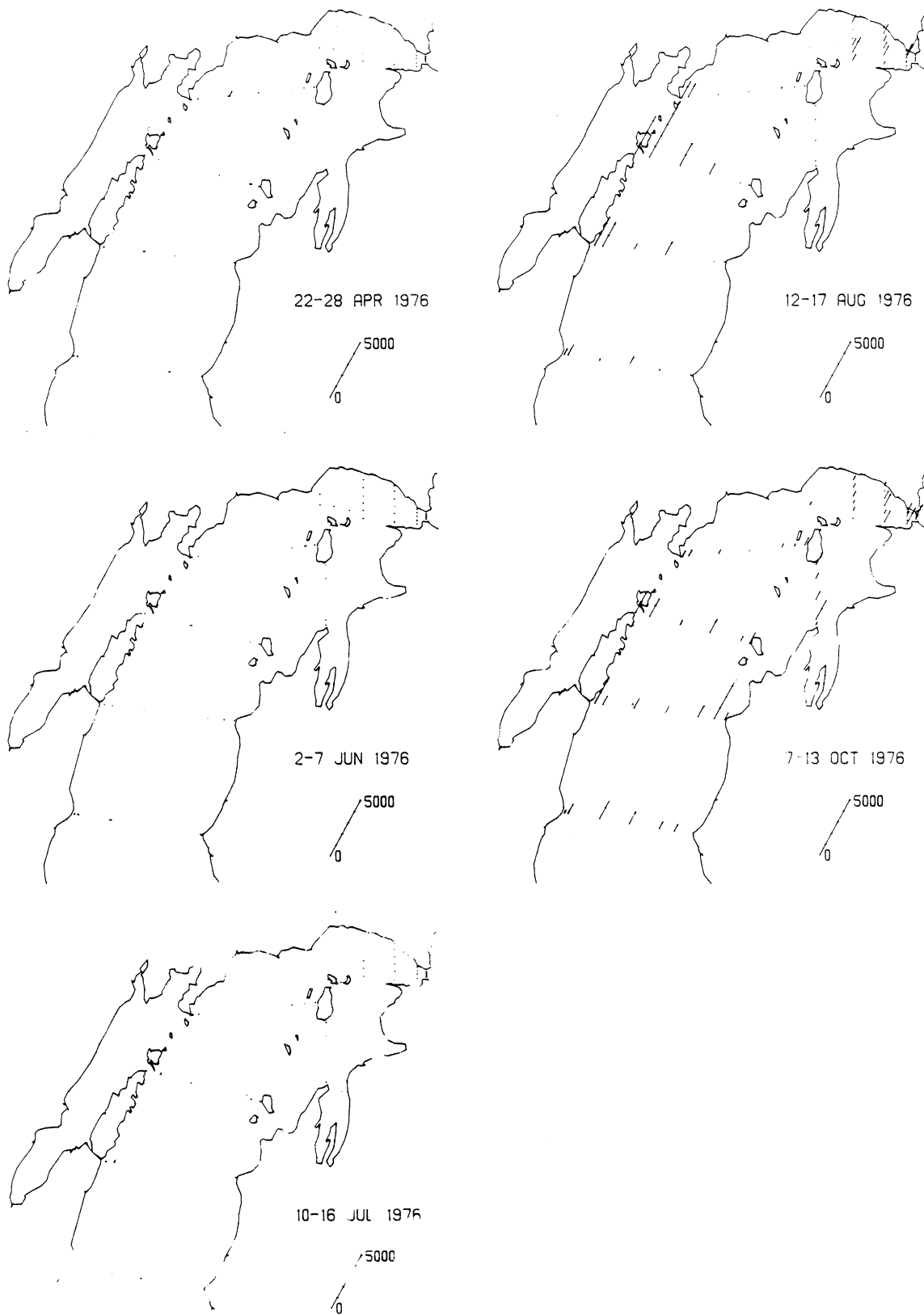


FIG. 79. Seasonal distribution of *Anacystis incerta*.

Lake Huron it is associated with the Saginaw Bay water mass, although it invades stations in the open lake late in the season. Its distribution in northern Lake Michigan is similar. Only small populations were found in April and June samples, but it became quite abundant at stations near Green Bay in August. By October it was generally distributed throughout the area sampled.

Anacystis thermalis (Menegh.) Dr. & Daily was considerably less abundant than A. incerta, but had a generally similar distribution pattern (Fig. 80). Significant populations first occurred at Station 29, near Death's Door, and in the Straits area in August and populations were generally distributed through northern Lake Michigan by October.

Schizothrix calcicola (Ag.) Gom. is one of the few blue-green algae which occurred in significant numbers early in the sampling season. It was present at most open-lake stations sampled in April, although highest abundance occurred at nearshore stations. Population densities increased in June, particularly at stations shoreward of the thermal bar. This was followed by a decline in July, with maximum population densities being found at midlake stations. Populations of this species did not recover significantly during the rest of the season sampled. Because individual cells are not resolvable, data for this species are reported as filaments/mL (Fig. 81).

The Cryptophyta, as a group, is a rather enigmatic component of phytoplankton assemblages in the Great Lakes. Their physiology is poorly known and their systematic affinities are not as clearly defined as those of members of most other groups. It appears that, unlike most other groups, the same species occur throughout the system. They tend to become more abundant in disturbed portions of the system and may be a dominant component of assemblages in highly eutrophied areas. In northern Lake Michigan (Fig. 82)

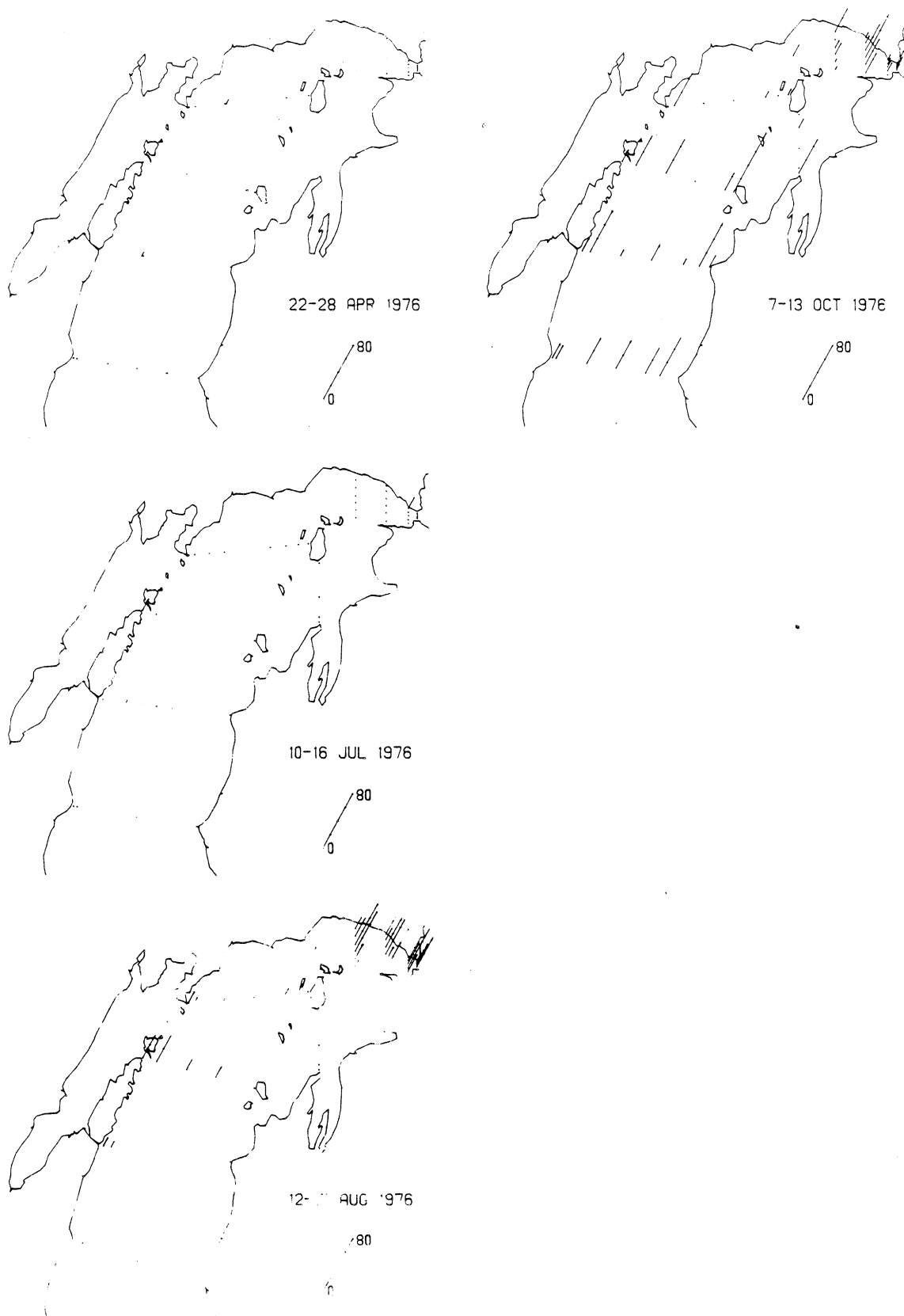


FIG. 80. Seasonal distribution of Anacystis thermalis.

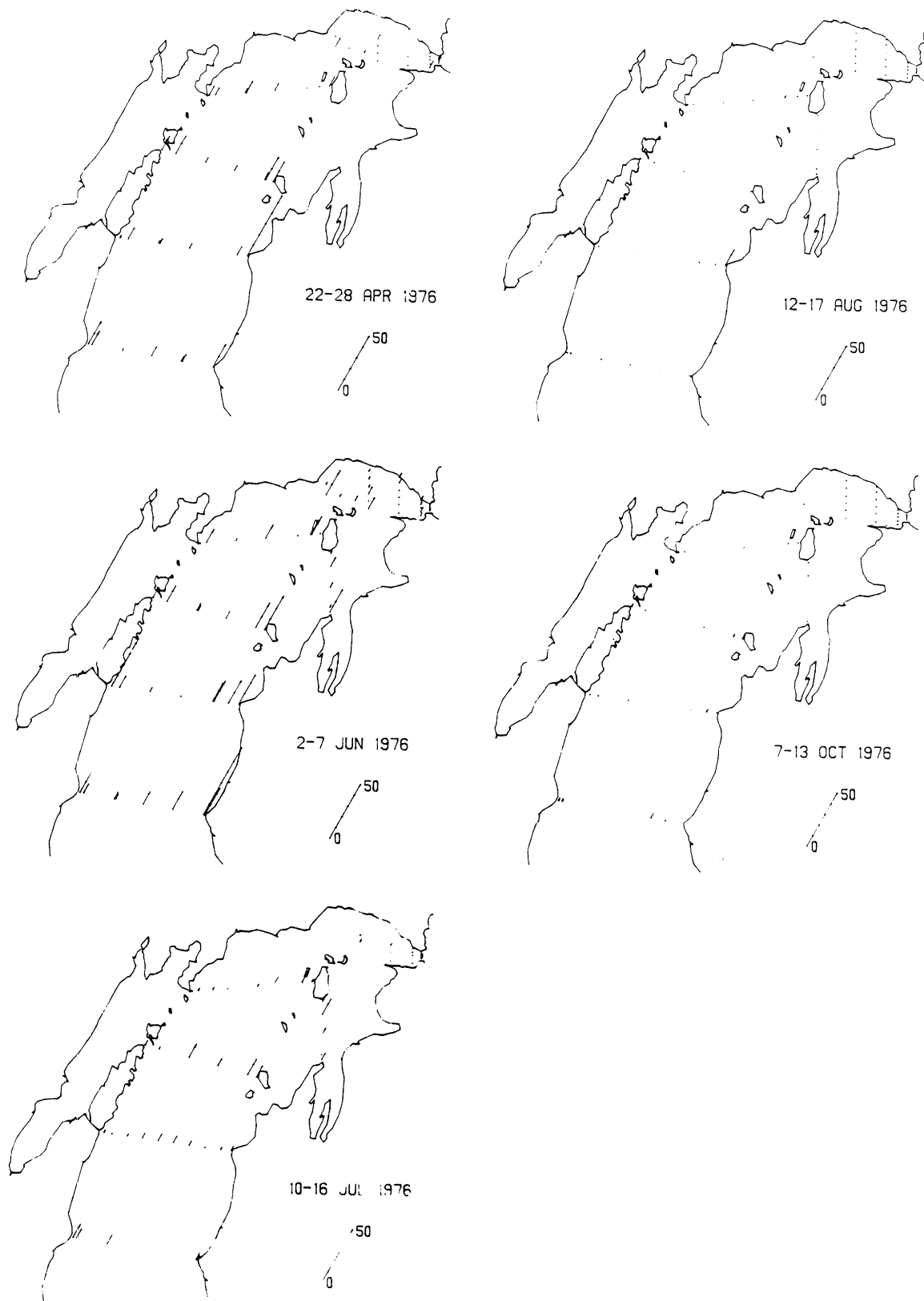


FIG. 81. Seasonal distribution of Schizothrix calcicola (filaments/mL).

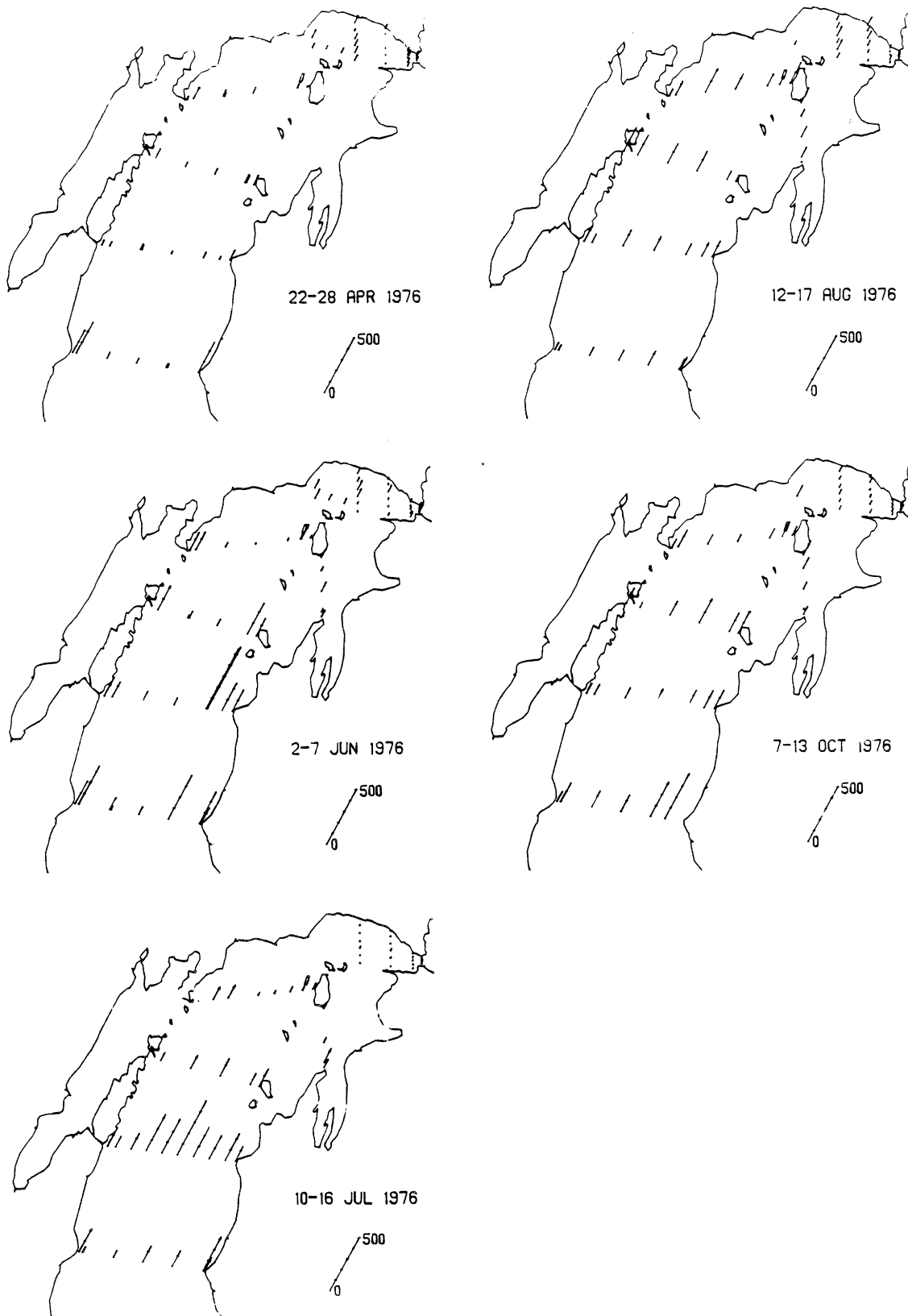


FIG. 82. Seasonal distribution of and abundance of cryptomonads (cells/mL).

they were present in near-surface phytoplankton samples collected in all areas at all seasons. They tended to follow the general pattern of phytoplankton abundance early in the year and were uniformly distributed during August and October. The only distinctive feature of their distribution is that they were consistently less abundant in the Straits area than in the rest of the region sampled.

The Pyrrophyta (dinoflagellates) are a numerically minor component of phytoplankton assemblages in northern Lake Michigan, but may be an important component of biomass because of the large cell size of some species. Scattered populations were found in April and June (Fig. 83), with highest densities occurring at stations in the Straits area. Maximum abundance at open-lake stations was found in July and only scattered small populations were noted at stations sampled during the last two cruises.

Large numbers of small flagellates of uncertain taxonomic affinities were present at all stations sampled throughout northern Lake Michigan (Fig. 84). Probably because of lack of taxonomic resolution, no distinct trends in distribution were noted in this composite group. Their seasonal pattern of abundance followed the general pattern of total phytoplankton abundance.

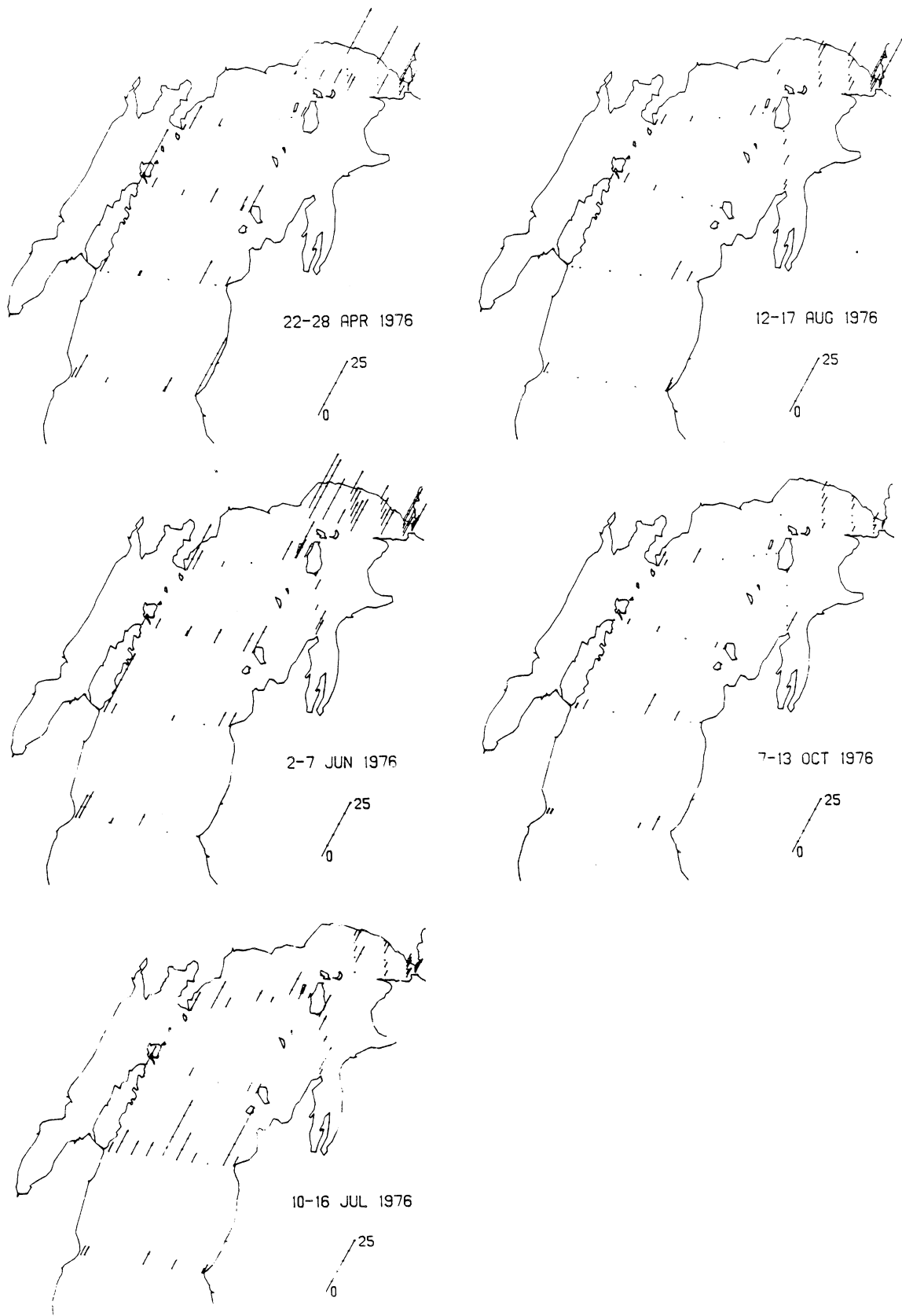


FIG. 83. Seasonal distribution and abundance of dinoflagellates (cells/mL).

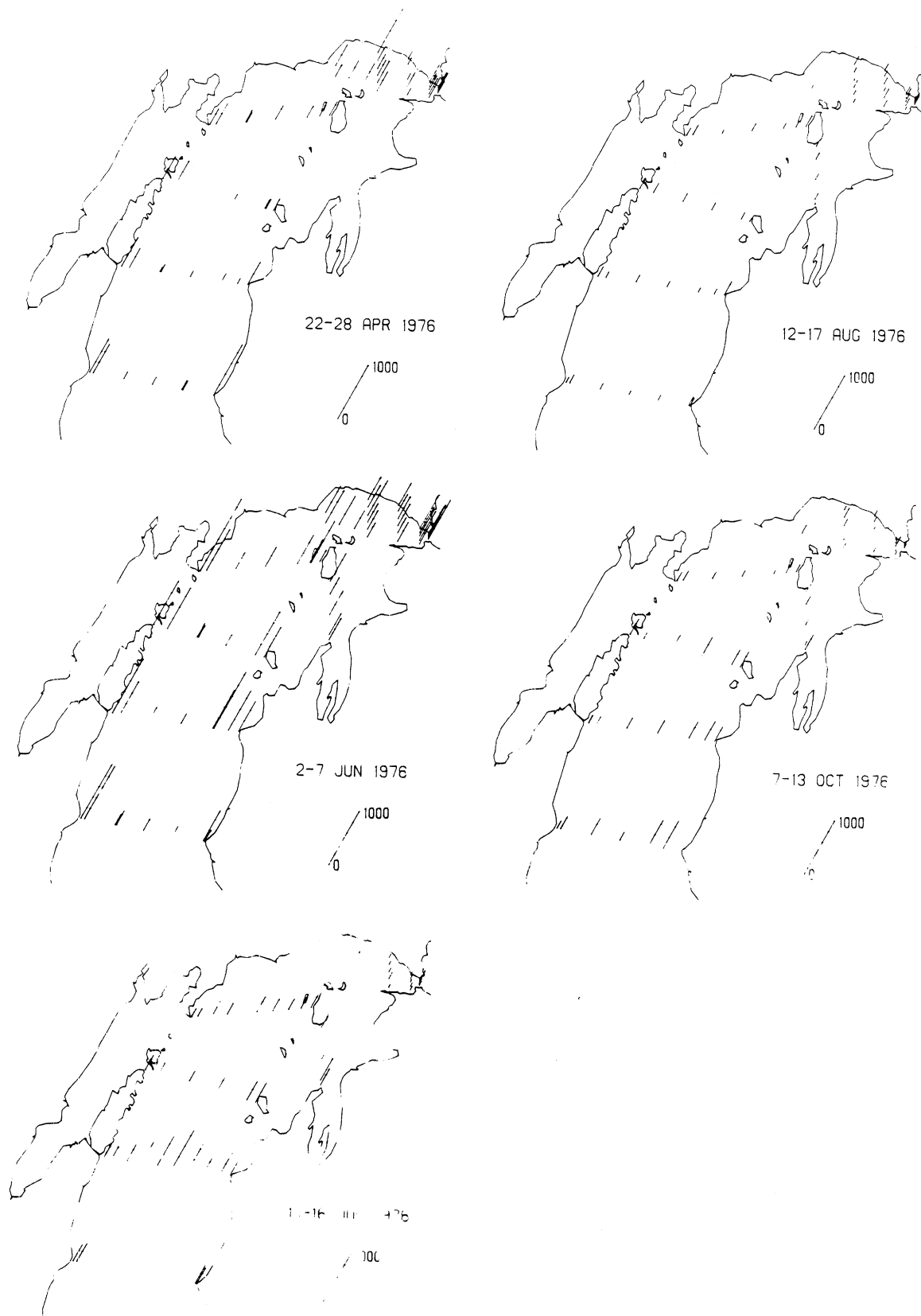


FIG. 84. Seasonal distribution and abundance of unidentified flagellates (cells/mL).

VERTICAL PHYTOPLANKTON DISTRIBUTION

The vertical distribution of phytoplankton populations was studied at Master Stations 6, 17, 25, and 36. These stations are located near the axis of the lake in deep water. The general pattern of total phytoplankton abundance, that of the major physiological groups, and particular species within major groups will be discussed. This information is important in a number of different respects. Survival in the hypolimnion is an important mechanism of maintaining some indigenous populations during periods of nutrient stress in the surface waters. It is becoming increasingly clear that gross modifications of vertical distribution is one of the consequences of eutrophication and that this may have serious implications for overall trophic dynamics of the system (Stoermer 1979). Comparison of vertical distribution profiles over time also give a first-order estimate of removal rates. It is quite clear that materials sequestered by certain populations are either recycled or transformed in the near-surface waters while materials sequestered by others may be transported directly to the sediment sink.

Vertical profiles of total phytoplankton abundance (Fig. 85) show that populations were evenly dispersed throughout the water column during the first two cruises. In July, a distinct subsurface abundance maximum had developed, although near-surface values remained relatively high. The differential between surface and maximum values was greatest on the southern transect at Station 6. By August, near-surface values had declined, particularly at the southern two stations, although subsurface values remained high. In October maxima redeveloped in the near-surface waters. It should be noted that there

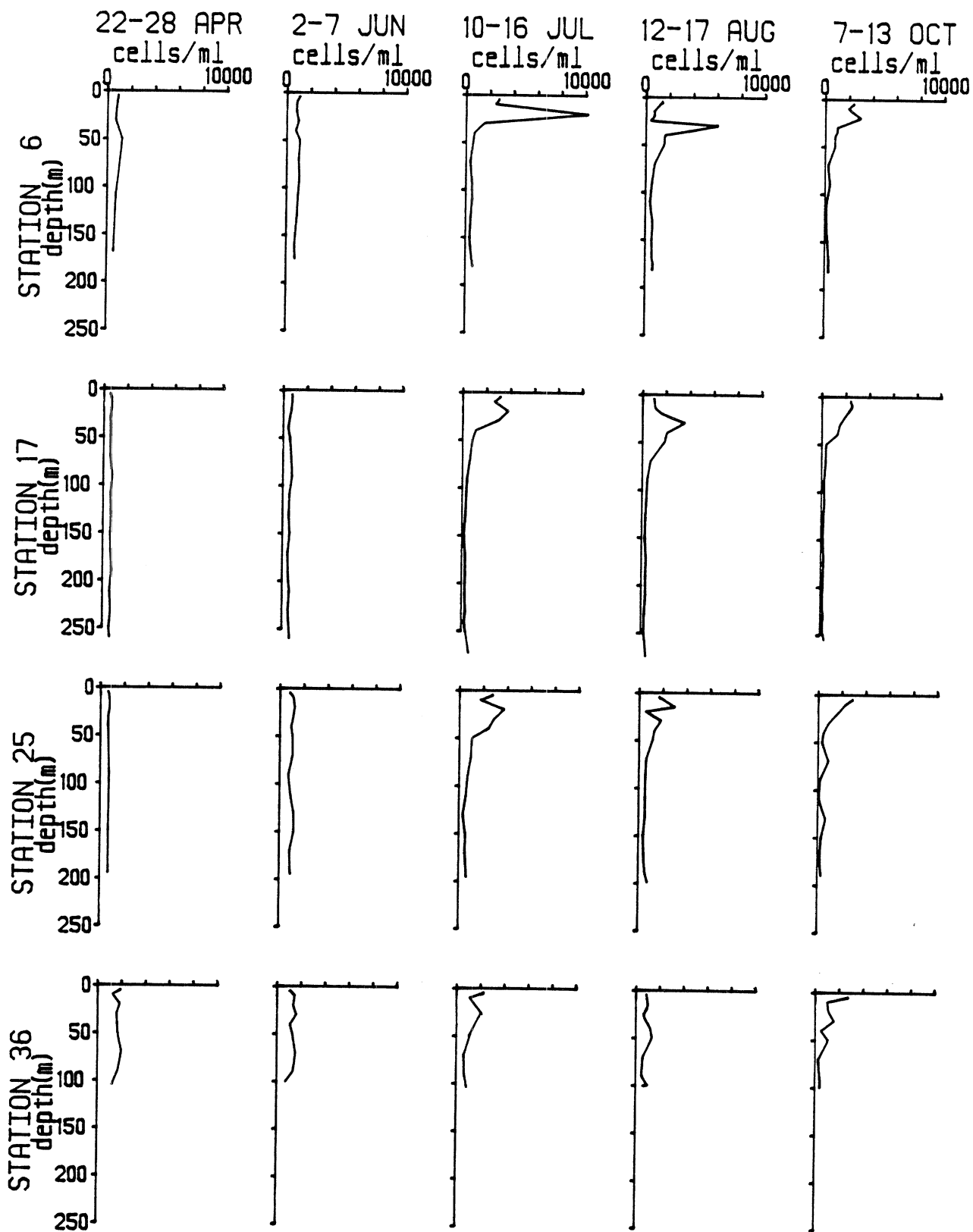


FIG. 85. Vertical distribution of total phytoplankton abundance.

was a qualitative difference in vertical distribution patterns between northern and southern stations throughout the year.

The general pattern for diatoms (Fig. 86) was for relatively uniform vertical distribution during the first two cruises, development of a near-surface maximum in July and a subsurface maximum in August, and return to more uniform vertical distribution in October. It should be noted that relatively high numbers of diatoms were present in deep water throughout the year.

Individual diatom species had some distinctive patterns. The vertical distribution of Asterionella formosa (Fig. 87) was erratic, with multiple peaks present in most profiles. During July, three of the four profiles showed relatively high numbers near the surface and a second peak in the region of the thermocline. By August only the deep maximum was present. It should also be noted that viable Asterionella cells were relatively rare in deep samples, indicating that this relatively lightly silicified species suffers considerable attrition during sinking.

In most cases, maximum abundance of Cyclotella comensis (Fig. 88) was found in the epilimnion or at thermocline depths. As was previously noted, this species appears particularly adapted to surviving very low levels of silica and has recently become more abundant in Lake Michigan. In contrast, more indigenous populations such as C. comta (Fig. 89) and C. ocellata (Fig. 90) were most abundant below the thermocline. It is also noteworthy that these populations were present in very low numbers, even at maximum development. The more eurytopic C. stelligera (Fig. 91) was one of the populations that strongly influenced the general diatom vertical distribution pattern because of its high abundance. It was uniformly distributed with depth during the first two cruises, most abundant at the surface in July and

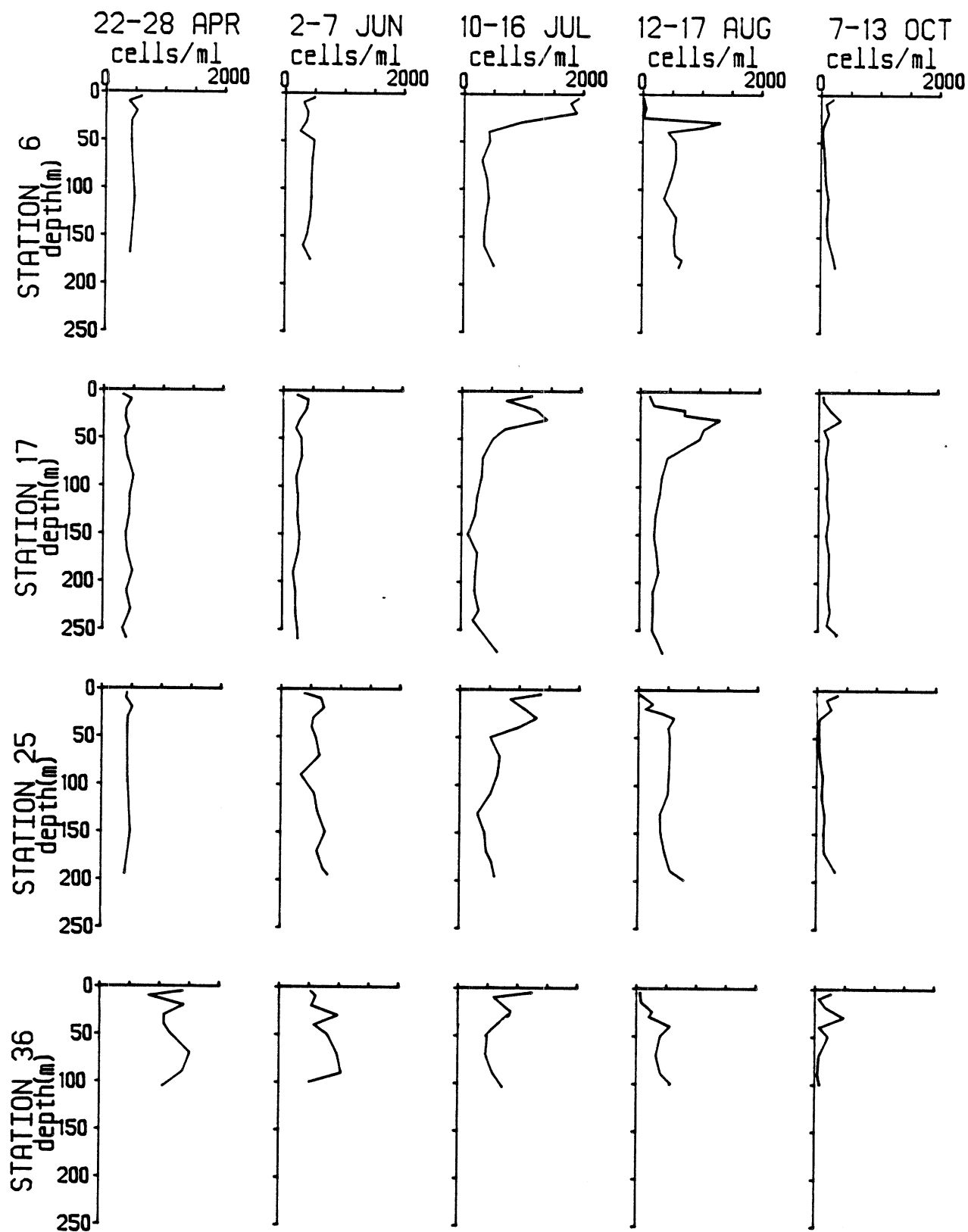


FIG. 86. Vertical distribution of diatoms.

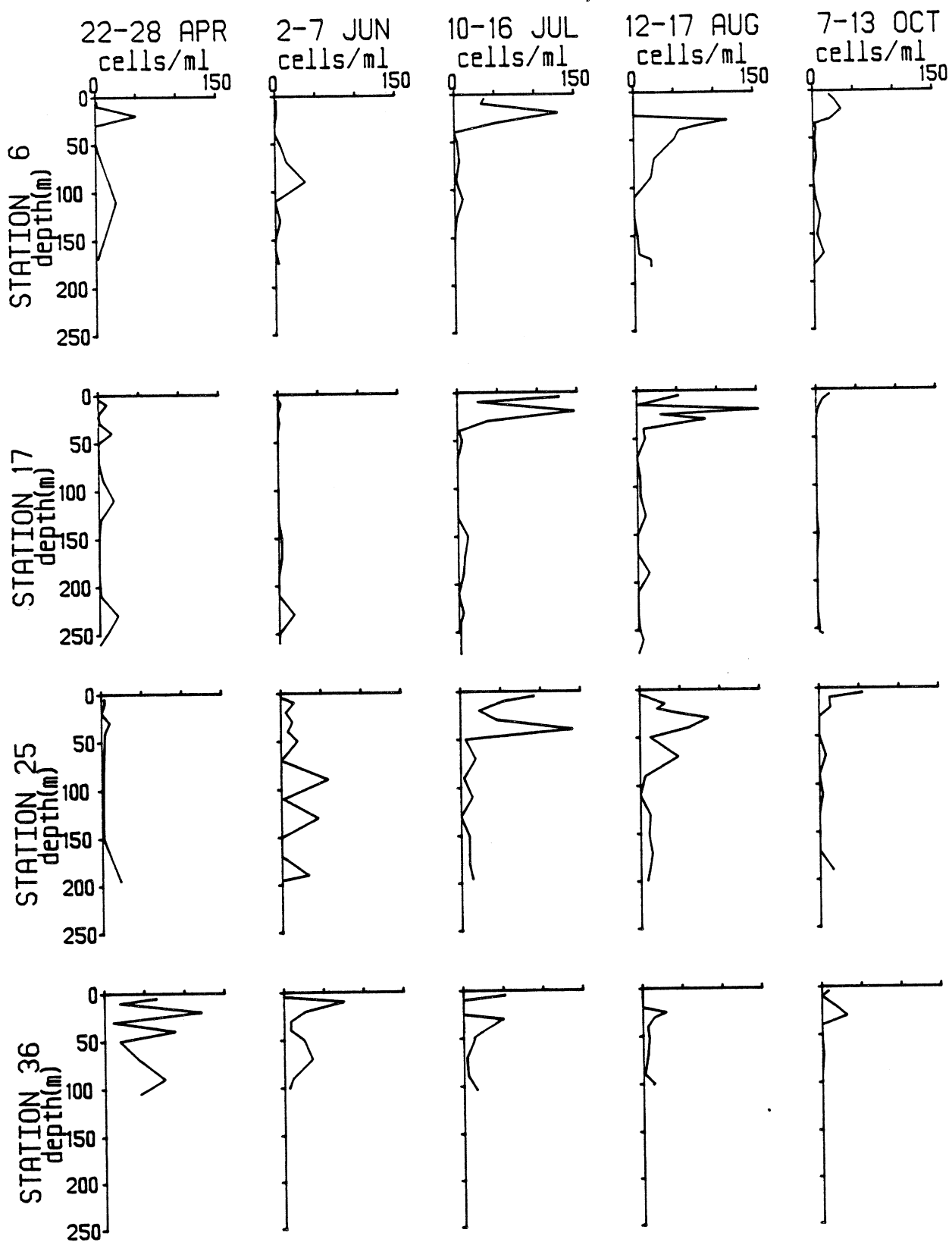


FIG. 87. Vertical distribution of *Asterionella formosa*.

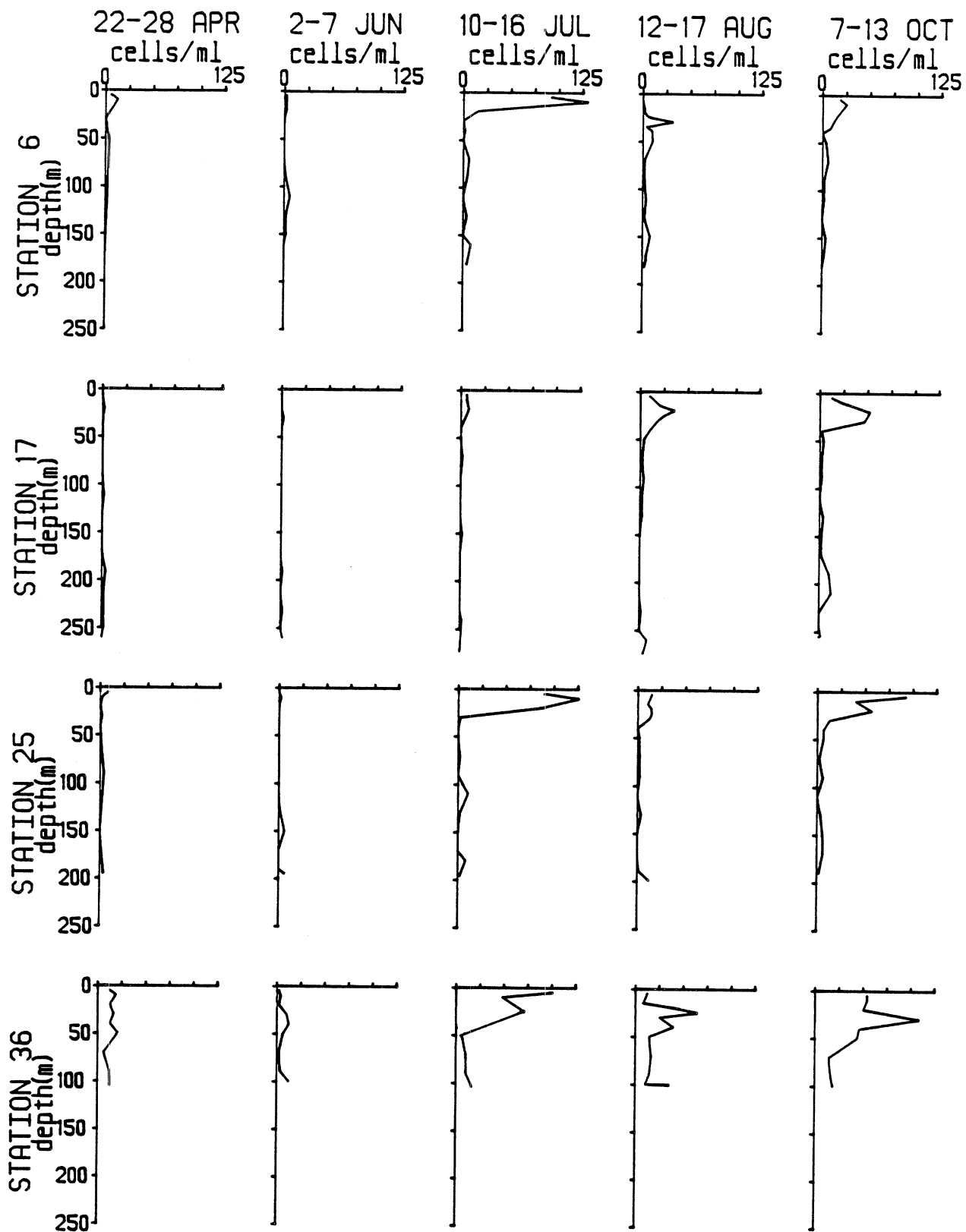


FIG. 88. Vertical distribution of Cyclotella comensis.

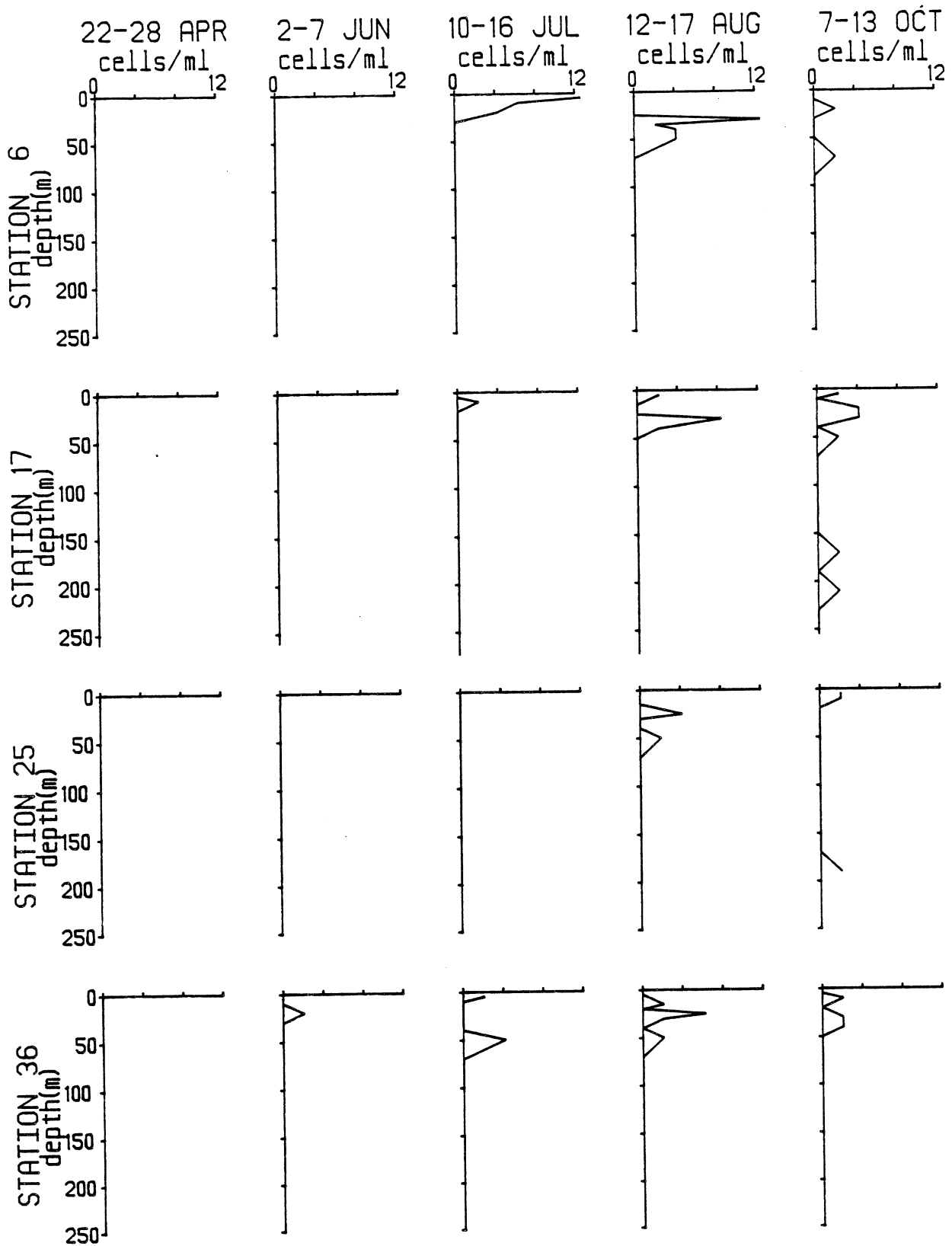


FIG. 89. Vertical distribution of *Cyclotella comta*.

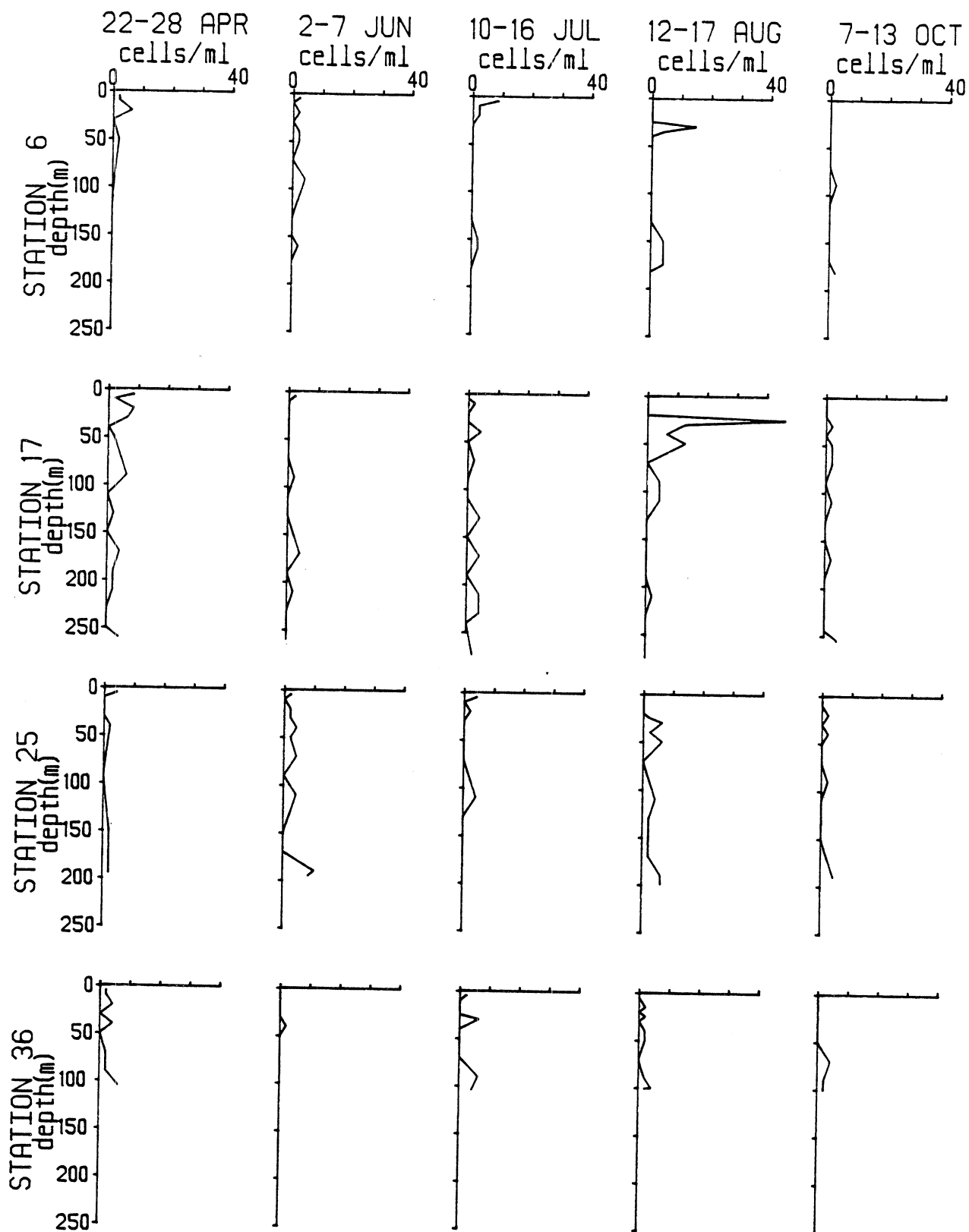


FIG. 90. Vertical distribution of Cyclotella ocellata.

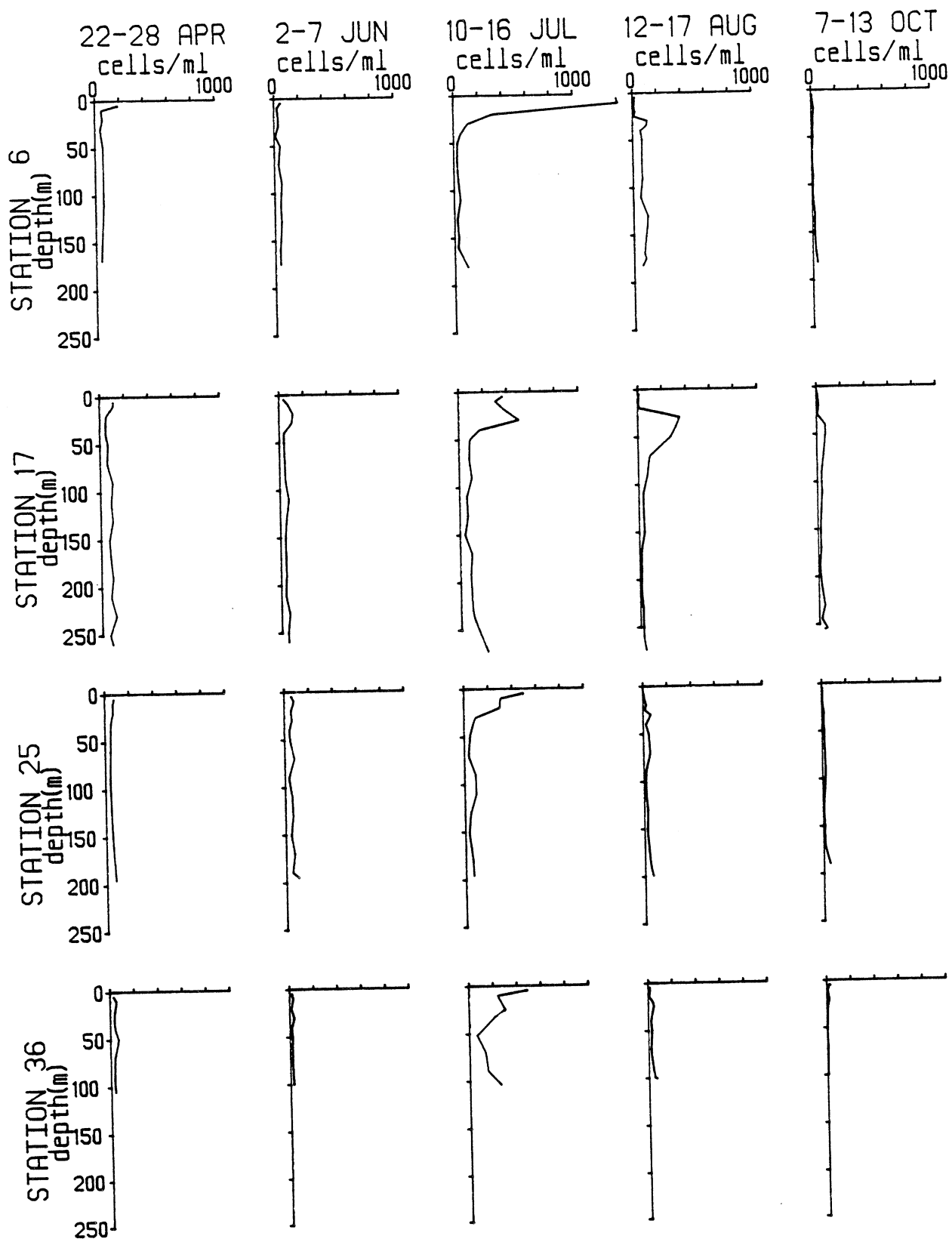


FIG. 91. Vertical distribution of Cyclotella stelligera.

had very low surface abundance with a deeper maximum in August. By October this species was reduced to very low abundance.

The distribution of Diatoma tenue var. elongatum (Fig. 92) was very erratic. At the stations where it occurred it had surface maxima in June and July and a subthermocline maximum in August.

The two species of Melosira which were major dominants in offshore phytoplankton assemblages had similar vertical distribution patterns. M. islandica (Fig. 93) had very limited abundance in near-surface waters after June, but significant quantities were present in the deep waters of northern stations until August. Melosira italica subsp. subarctica was both more abundant and more persistent (Fig. 94). Populations were fairly uniformly distributed through the water column during the first two cruises. Near-surface populations declined by July, but significant quantities of this entity were found below the thermocline through the rest of the sampling period. It should be noted that the deep maxima of M. islandica tended to be most highly developed at northern stations. The persistence of both species below the thermocline is striking.

The opposite trend was shown by two species of Rhizosolenia abundant in our samples (Figs. 95 and 96). Both developed large subthermocline maxima, but the relatively fragile cells, particularly of R. eriensis, did not persist in deep water. Maximum abundance of R. gracilis was found earlier and its cells tended to survive sinking to a greater extent.

The vertical distribution of two small species of Stephanodiscus showed an interesting and somewhat unusual trend (Figs. 97 and 98). Both were uniformly distributed through the water column during the first two cruises, but were reduced to a minimal abundance in the surface waters by July.

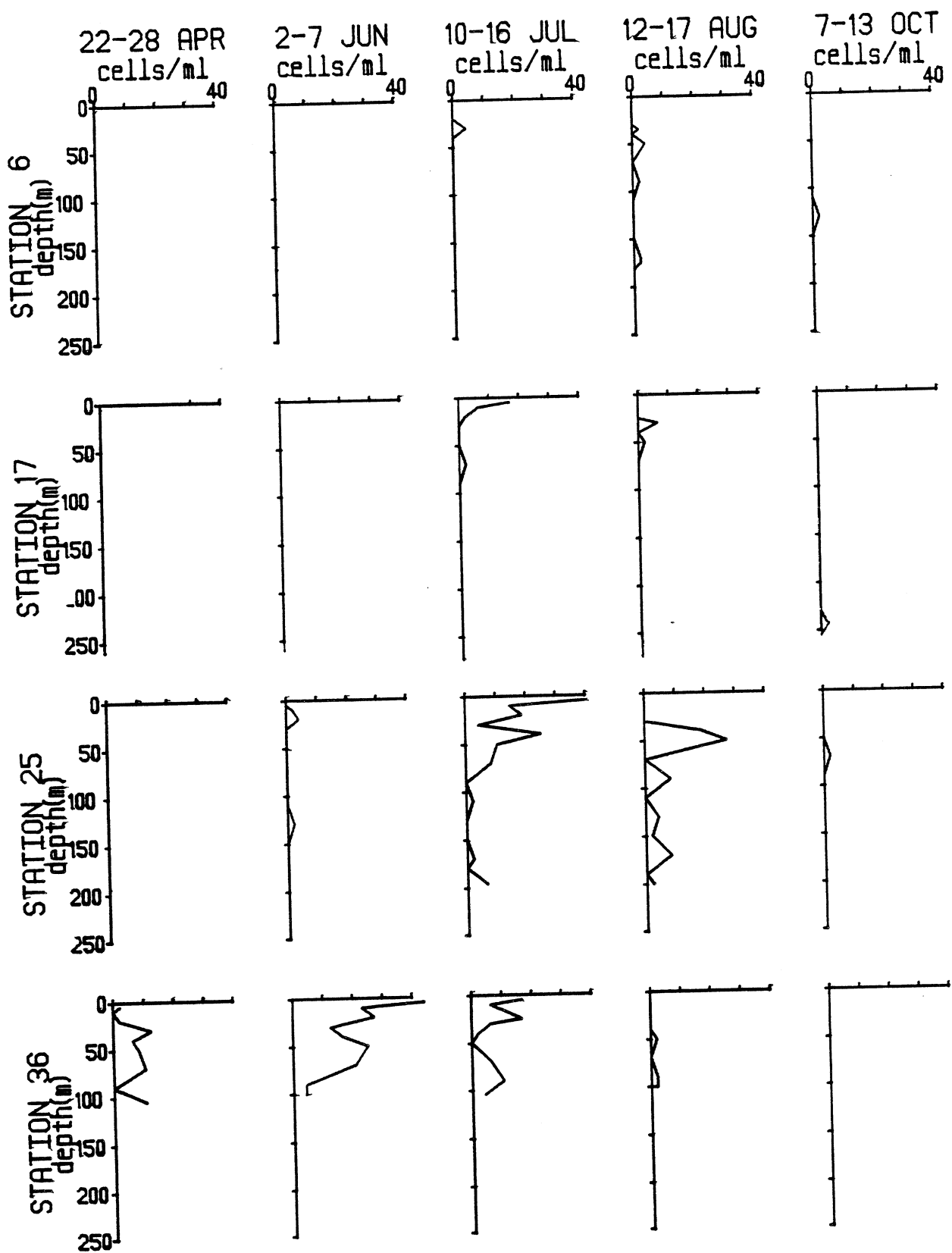


FIG. 92. Vertical distribution of *Diatoma tenue* var. *elongatum*.

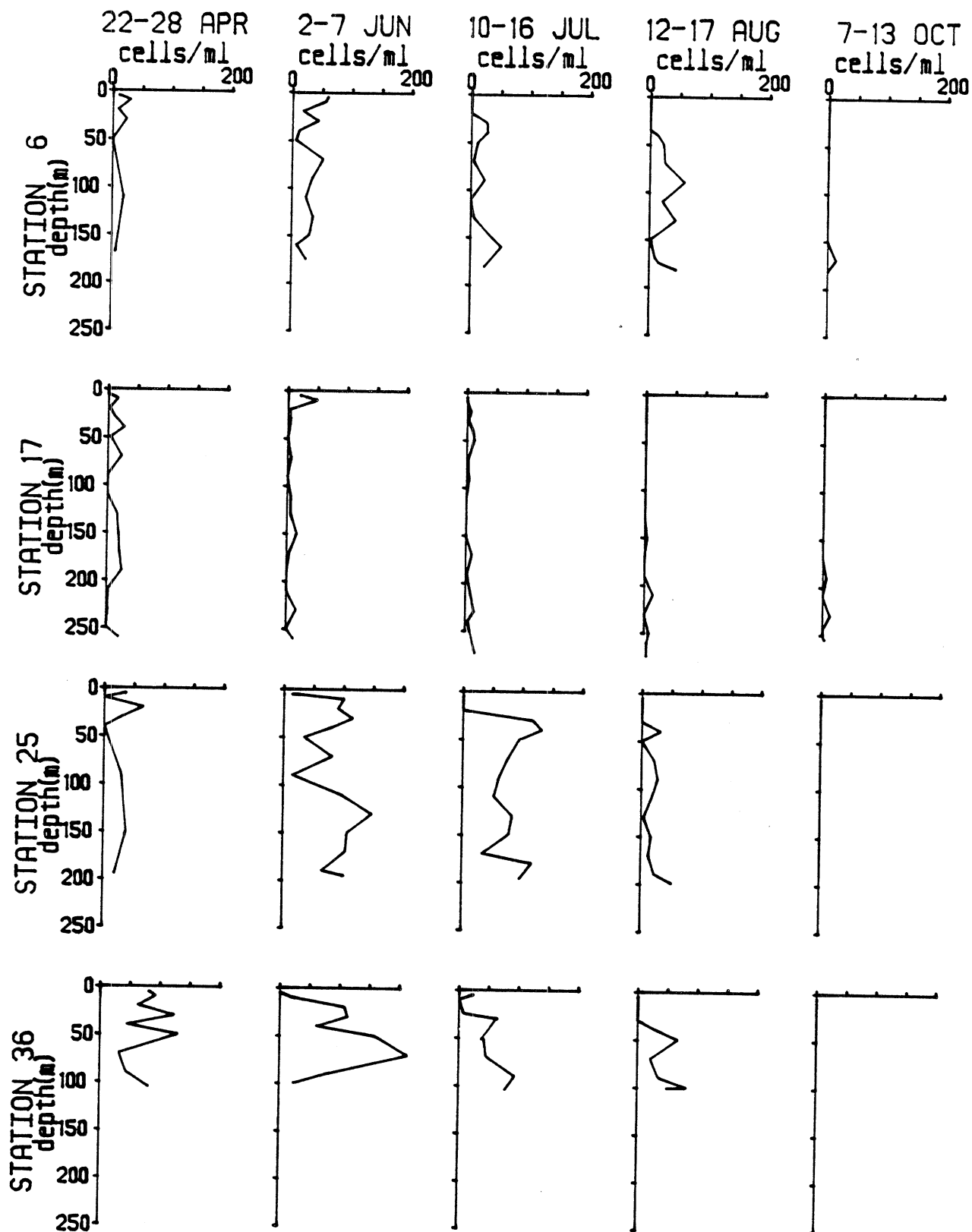


FIG. 93. Vertical distribution of Melosira islandica.

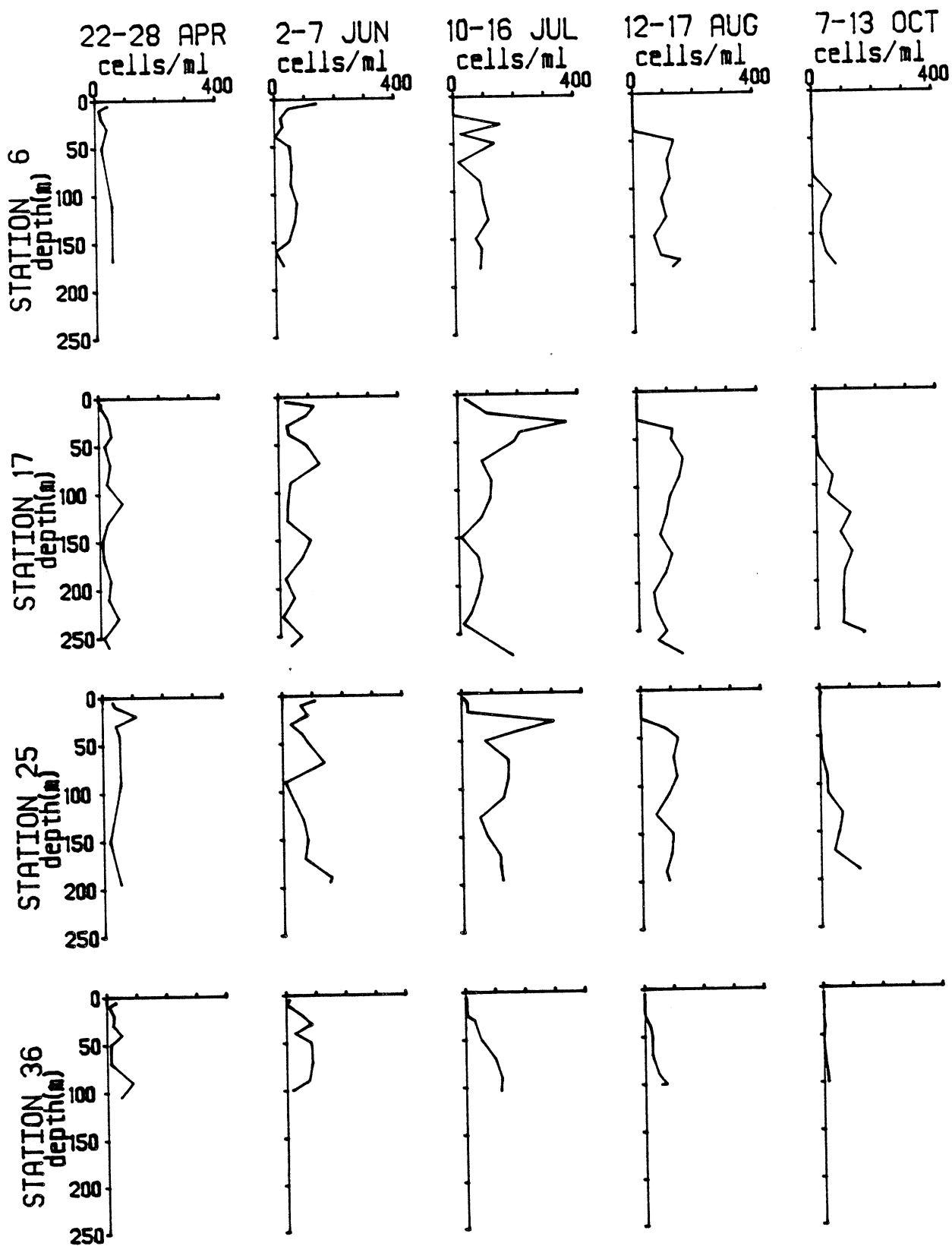


FIG. 94. Vertical distribution of *Melosira italica* subsp. *subarctica*.

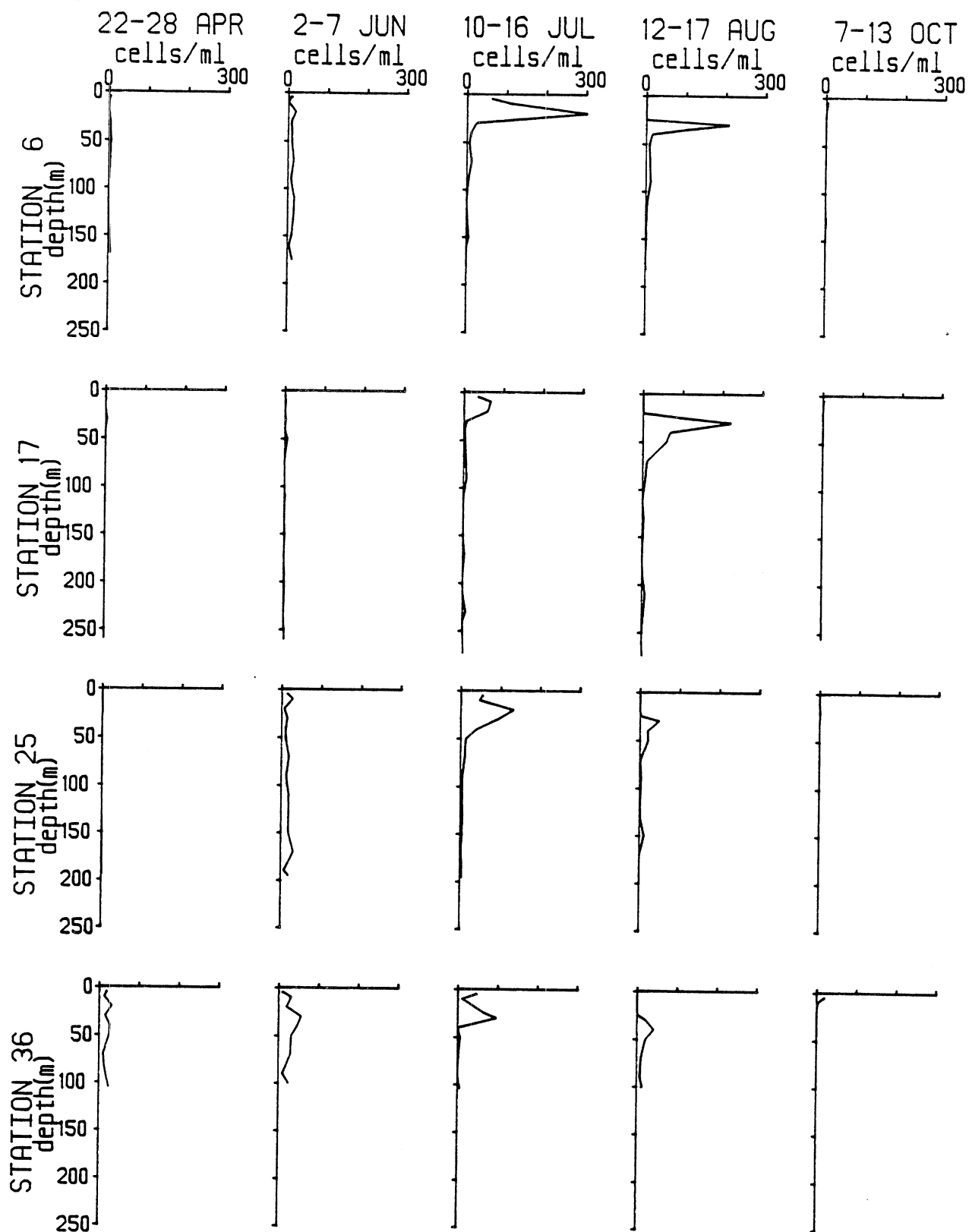


FIG. 95. Vertical distribution of Rhizosolenia eriensis.

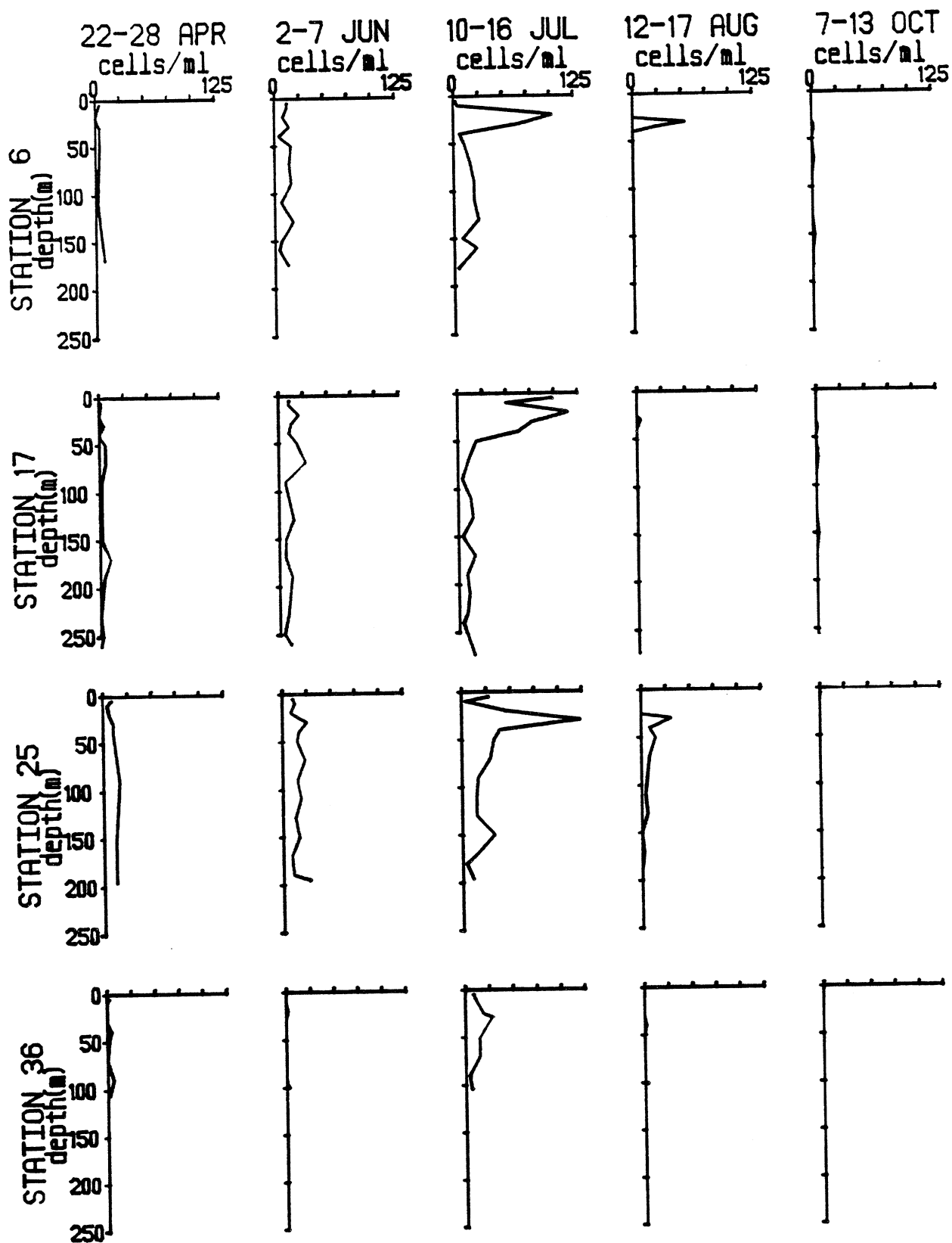


FIG. 96. Vertical distribution of *Rhizosolenia gracilis*.

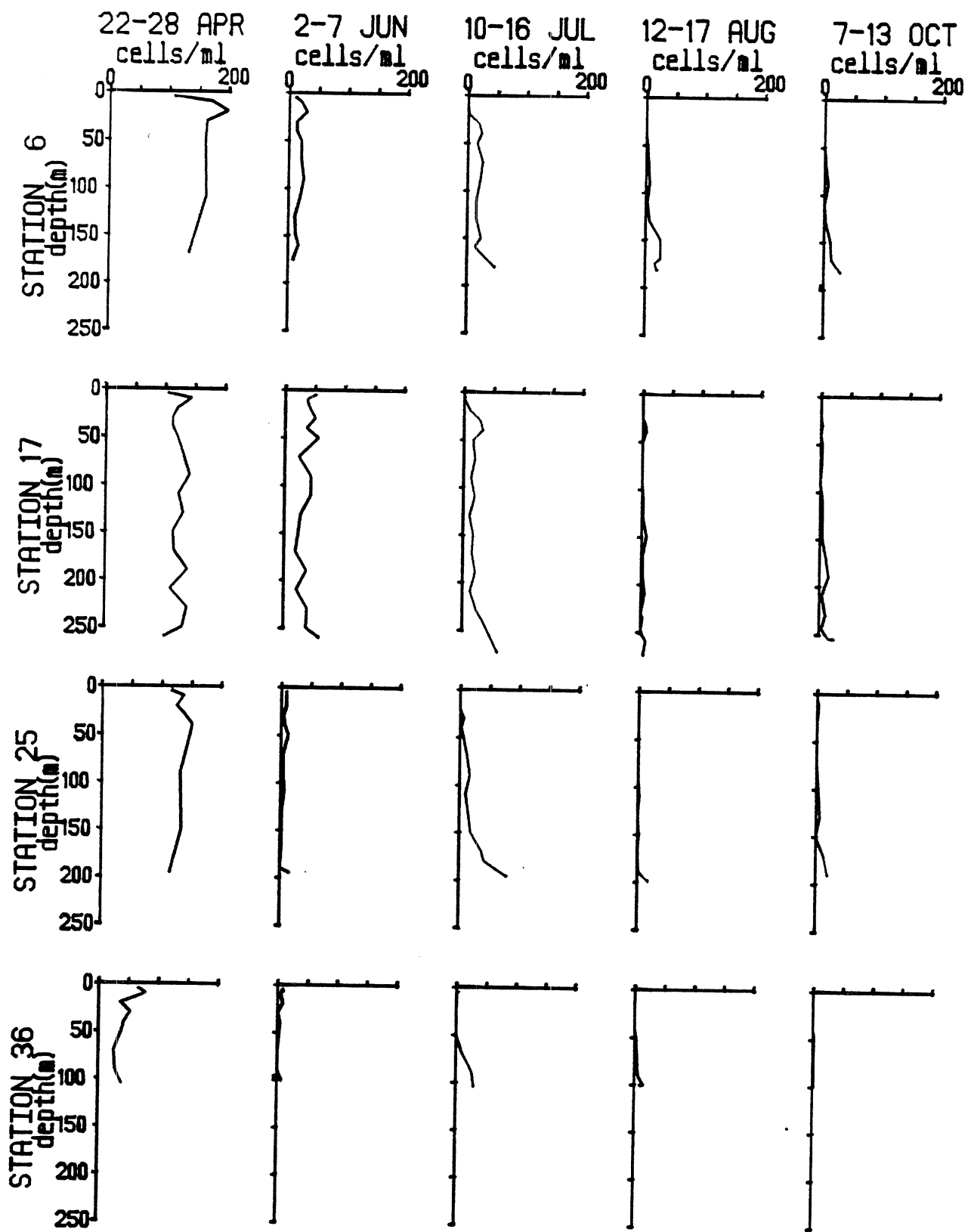


FIG. 97. Vertical distribution of Stephanodiscus hantzschii.

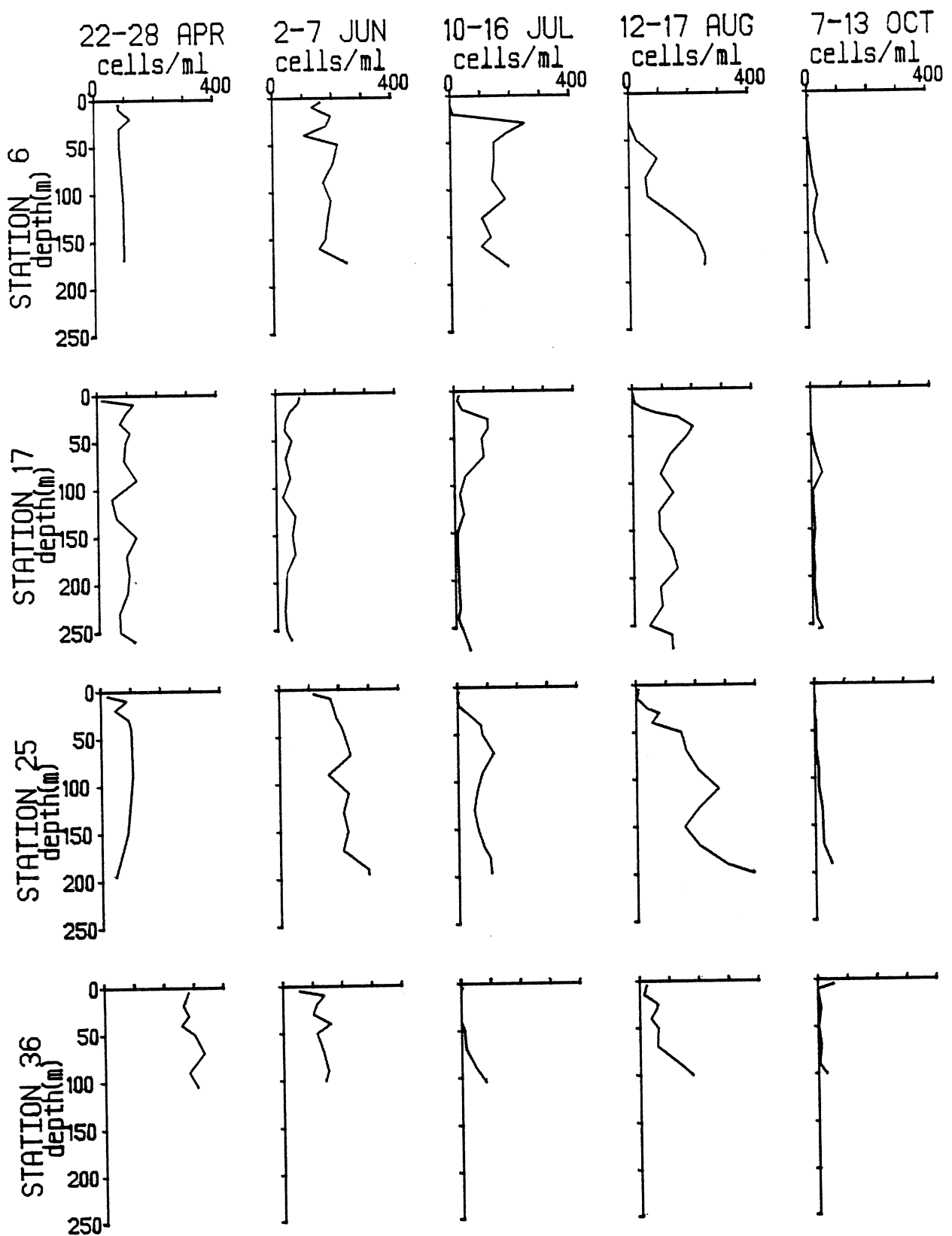


FIG. 98. Vertical distribution of *Stephanodiscus minutus*.

In several profiles both showed a monotonic increase in abundance with depth following stratification. Stephanodiscus hantzschii was more abundant at southern stations and declined more rapidly after stratification than did S. minutus.

Of the three dominant species of Synedra in our samples, S. filiformis (Fig. 99) was most abundant, had the most highly developed deep maxima, and was the least persistent in deep samples. It is also the least morphologically robust. Synedra delicatissima var. angustissima, (Fig. 100), which has somewhat more strongly silicified valves, was more abundant in deep samples. Largest populations of S. ostenfeldii (Fig. 101), a more eutrophication-tolerant form, were found in the epilimnion and few viable cells were found in deep samples.

The vertical distribution of Tabellaria flocculosa var. linearis (Fig. 102) was erratic, similar to Diatoma tenue var. elongatum which has the same growth habit, but all stations had subthermocline maxima in August.

The vertical distribution of green algae in northern Lake Michigan had a number of interesting and rather unusual aspects. The plot of total abundance for this group (Fig. 103) shows that a very pronounced deep maximum developed in July which moved downward in August. This presents a somewhat distorted picture of behavior of this group, because it mostly represents the extreme abundance of a small filamentous green alga of uncertain systematic affinities (green filament sp. #5; Fig. 104), particularly at Station 6. We have not previously noted abundant occurrences of this species in Lake Michigan, but it is extremely abundant in Saginaw Bay and at some stations in Lake Huron which are influenced by the Saginaw Bay water mass (Stoermer and Kreis 1980). Other species showed different vertical distribution patterns. Both Ankistrodesmus

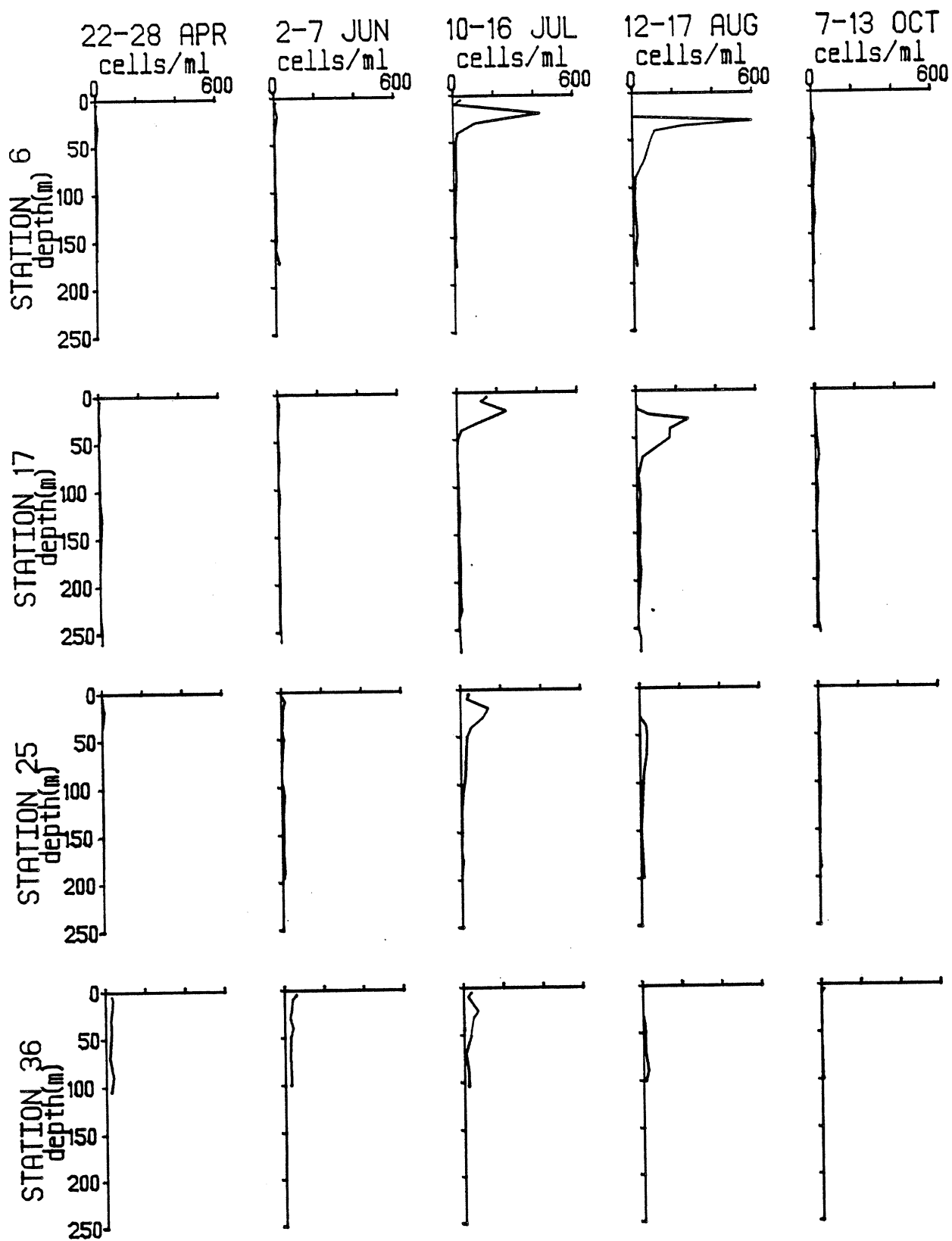


FIG. 99. Vertical distribution of *Synedra filiformis*.

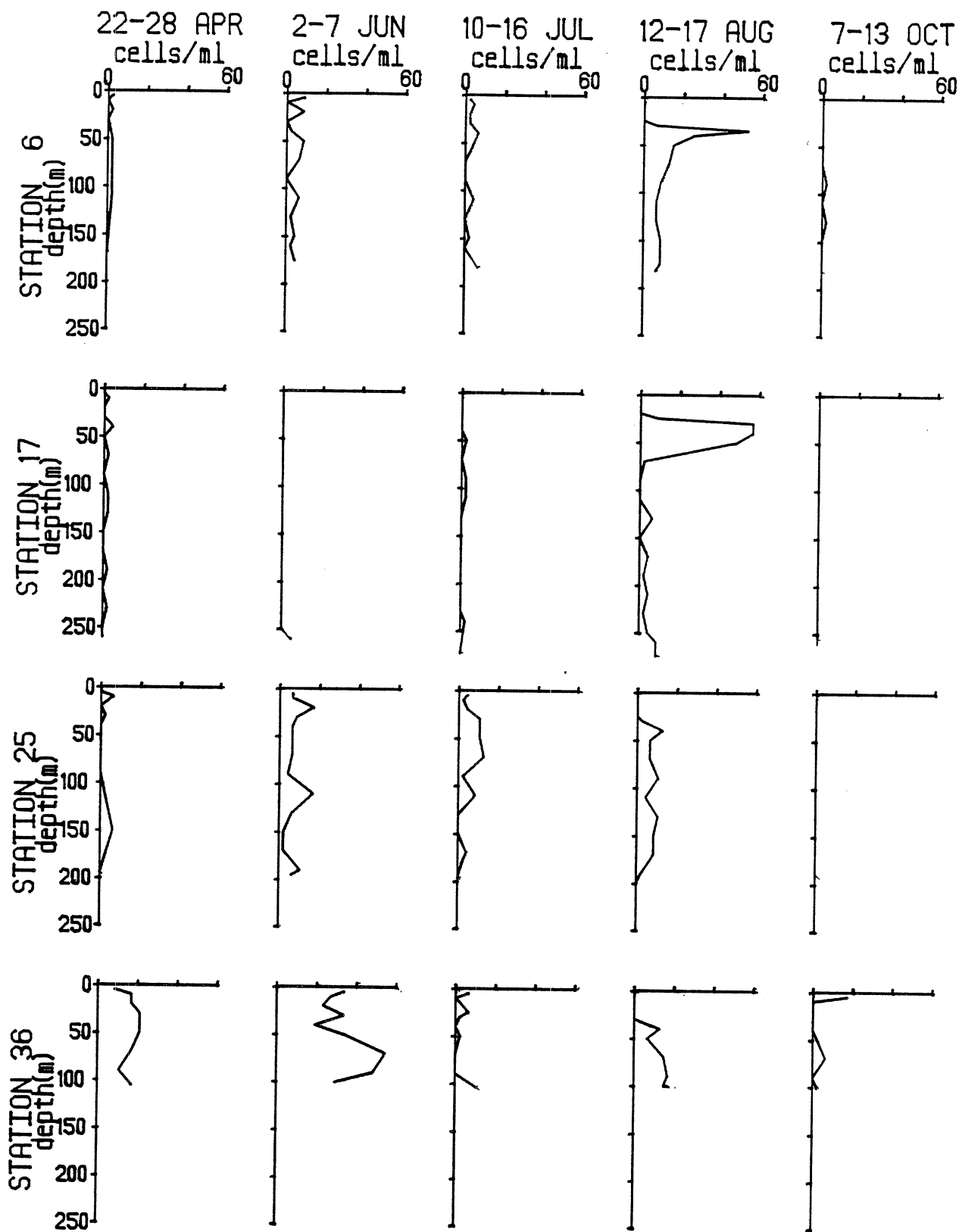


FIG. 100. Vertical distribution of *Synedra delicatissima* var. *angustissima*.

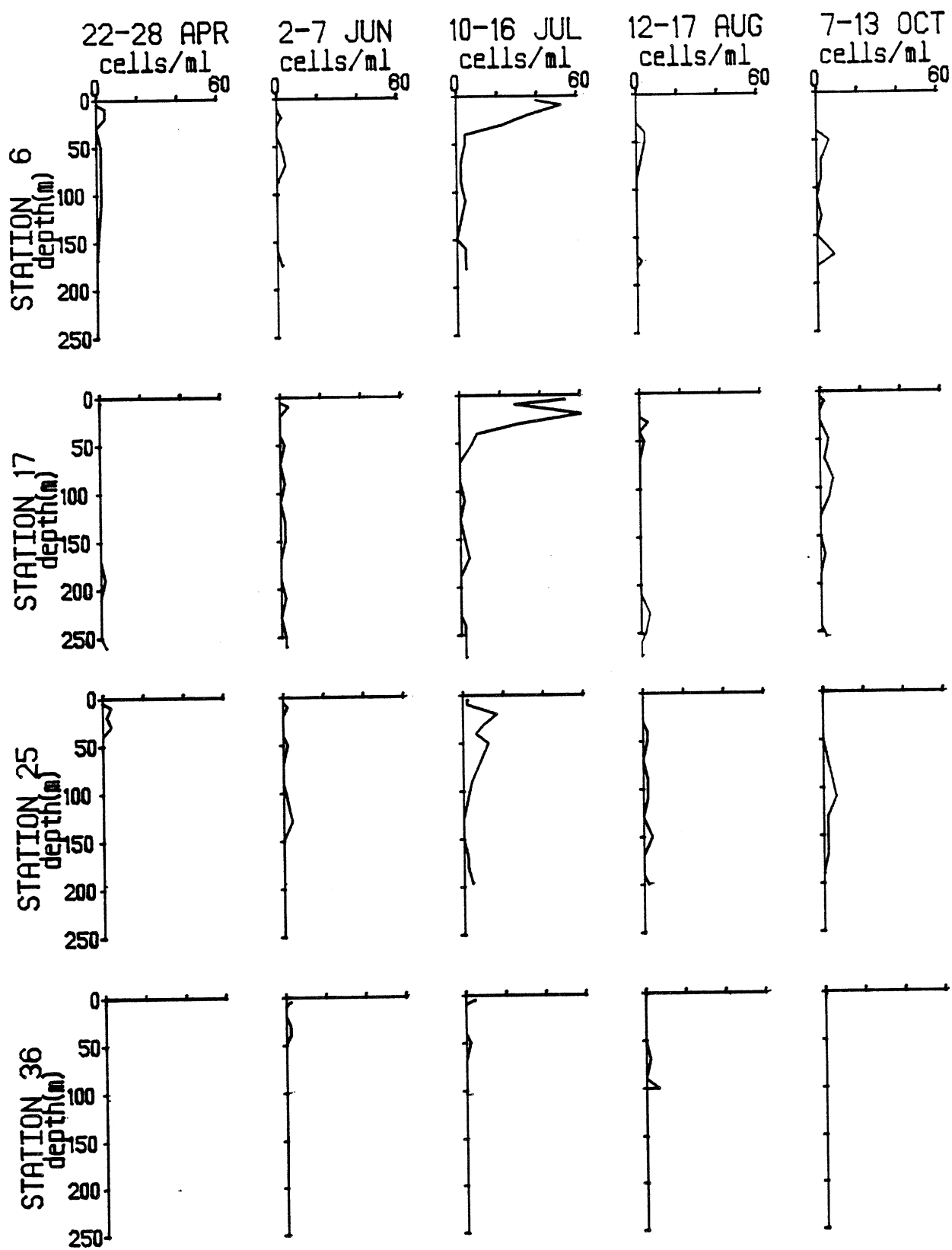


FIG. 101. Vertical distribution of Synedra ostenfeldii.

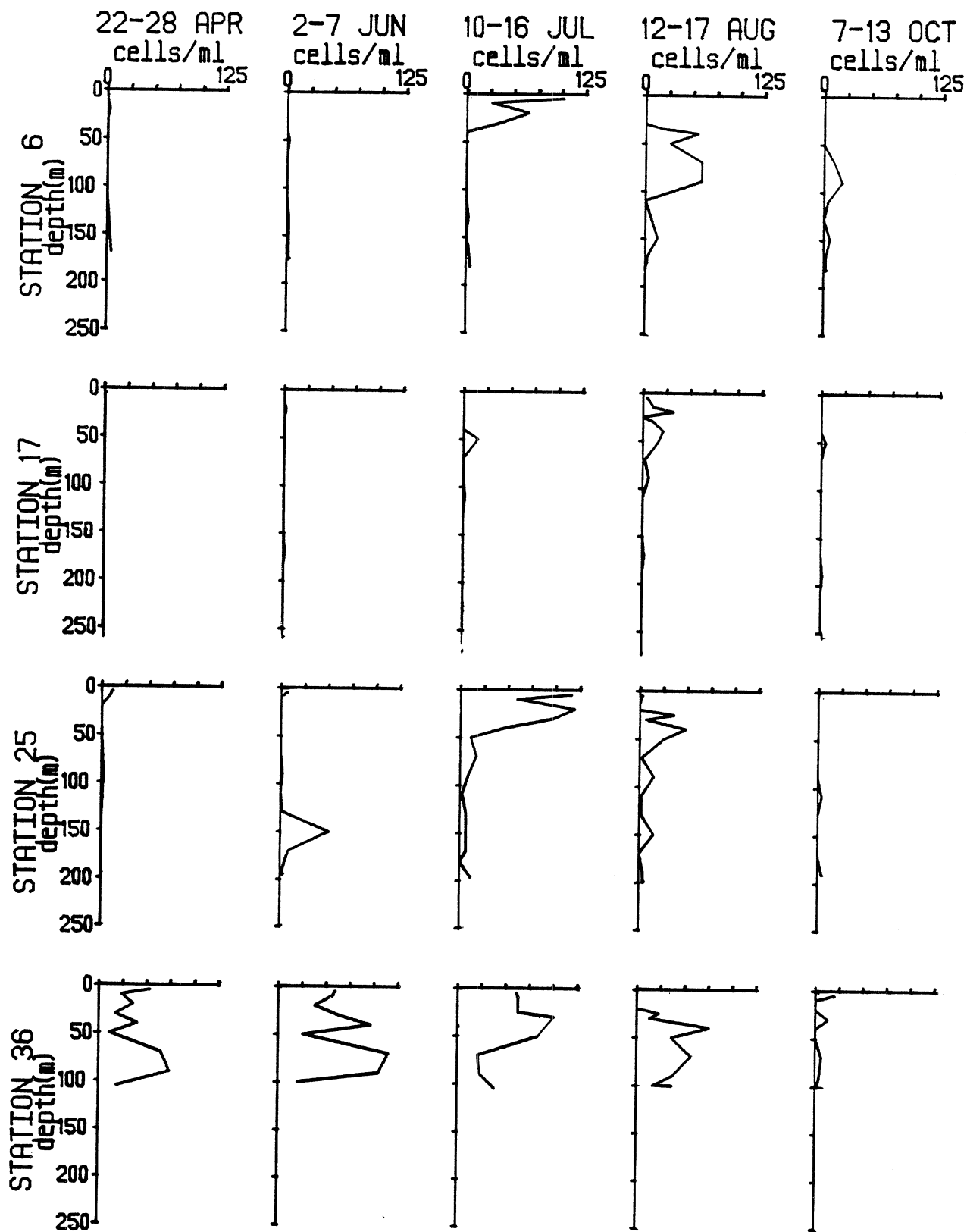


FIG. 102. Vertical distribution of Tabellaria flocculosa var. linearis.

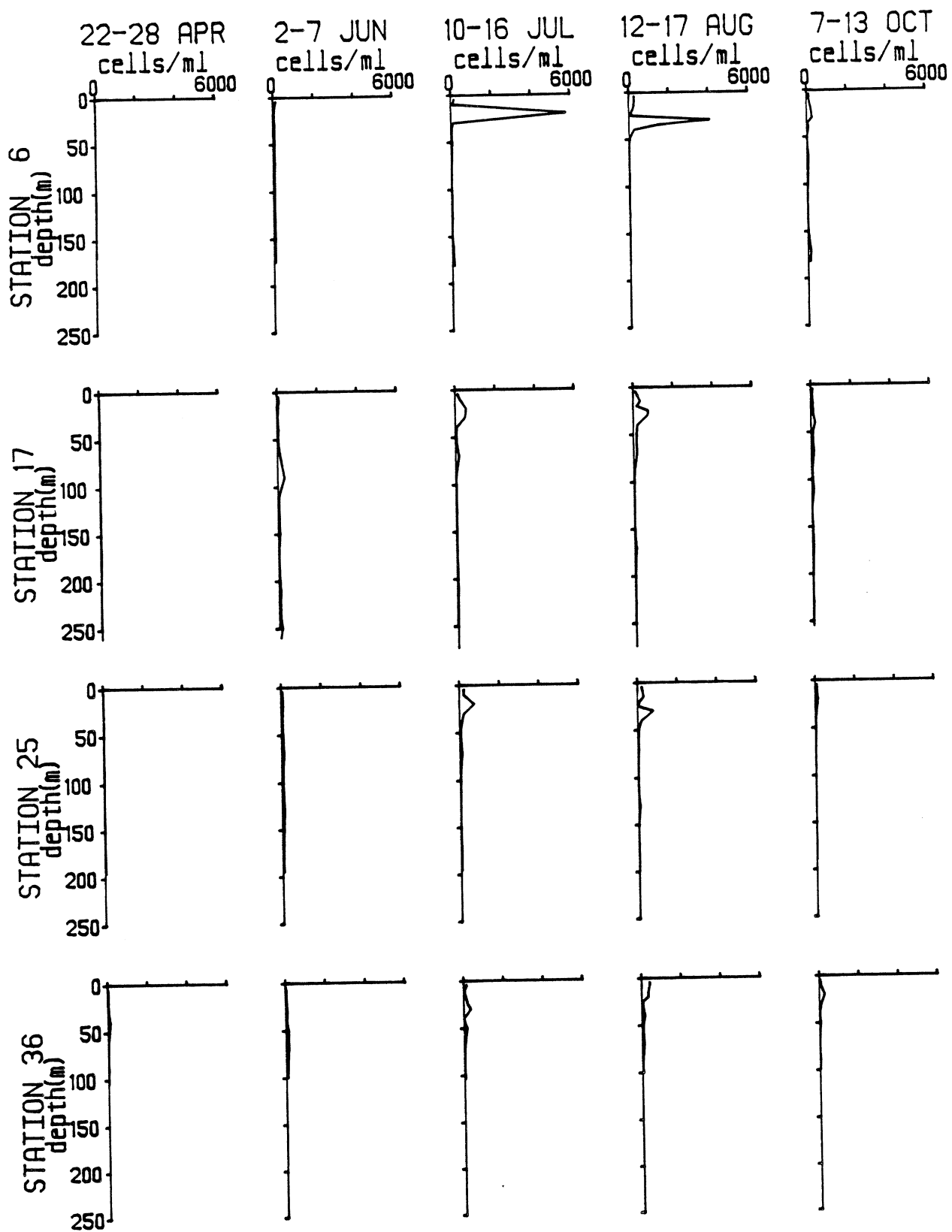


FIG. 103. Vertical distribution of green algae.

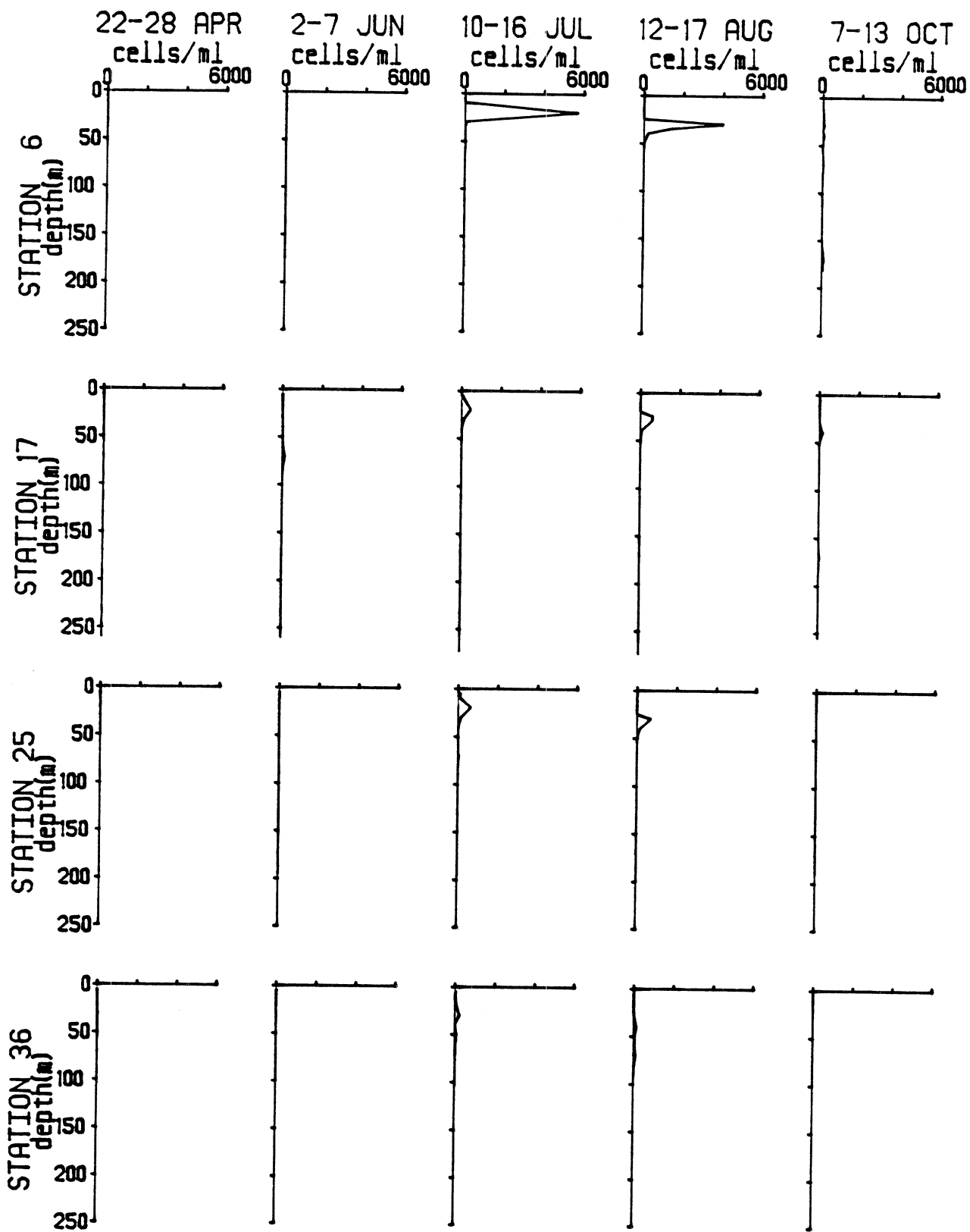


FIG. 104. Vertical distribution of green filament sp. #5.

falcatus (Fig. 105) and Scenedesmus bicellularis (Fig. 106) were uniformly distributed through the water column on the basis of samples taken during the first two cruises. After July, populations were much reduced in the near-surface waters and maxima developed at subthermocline depth. Both taxa persisted in deep samples, which is remarkable in light of the small size and relatively fragile structure of the cells. On the other hand, populations of Ankistrodesmus sp. #6 (Fig. 107) were largely restricted to epilimnetic waters.

As might be expected, the general pattern of vertical distribution for blue-green algae (Fig. 108) was dominated by populations abundant in the near-surface waters in late summer and fall. This was true of dominant populations such as Anacystis incerta (Fig. 109) and Anacystis thermalis (Fig. 110). Schizothrix calcicola (Fig. 111), however, was most abundant early in the sampling period, and persisted only at depths near the thermocline.

Chrysophytes (Fig. 112) were uniformly distributed through the water column during the first two cruises, formed pronounced deep peaks in abundance in July, declined in August, and tended to redevelop in the near-surface waters in October. The dominant population contributing to this trend was Ochromonas spp. (Fig. 113).

Unlike most of the other groups, the Cryptomonads (Fig. 114) consistently had highest abundance in the epilimnion following stratification. This was true of the larger species of Cryptomonas (Fig. 115) and of smaller species such as Rhodomonas minuta Skuja (Fig. 116) and R. minuta var. nannoplanctica Skuja (Fig. 117).

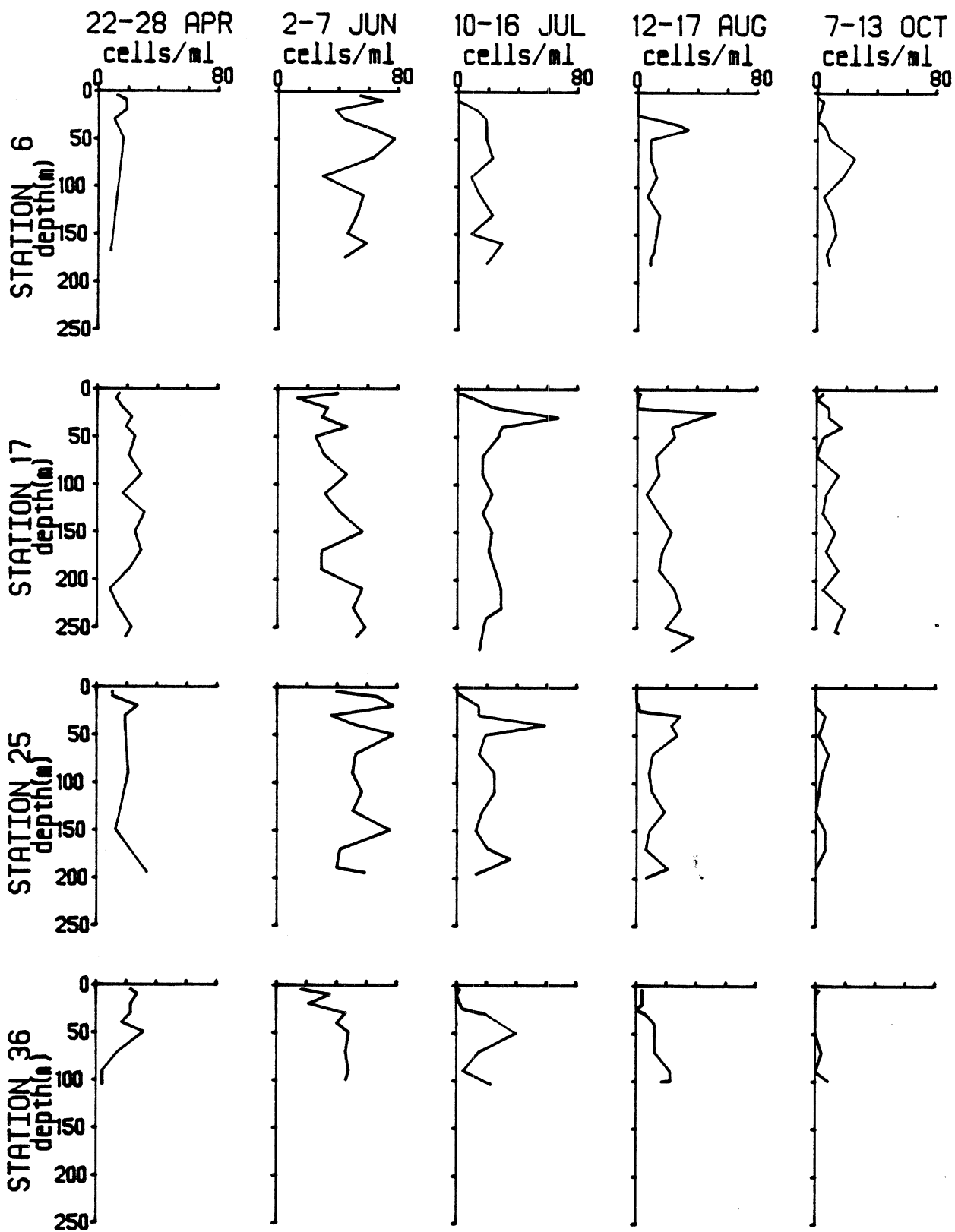


FIG. 105. Vertical distribution of Ankistrodesmus falcatus.

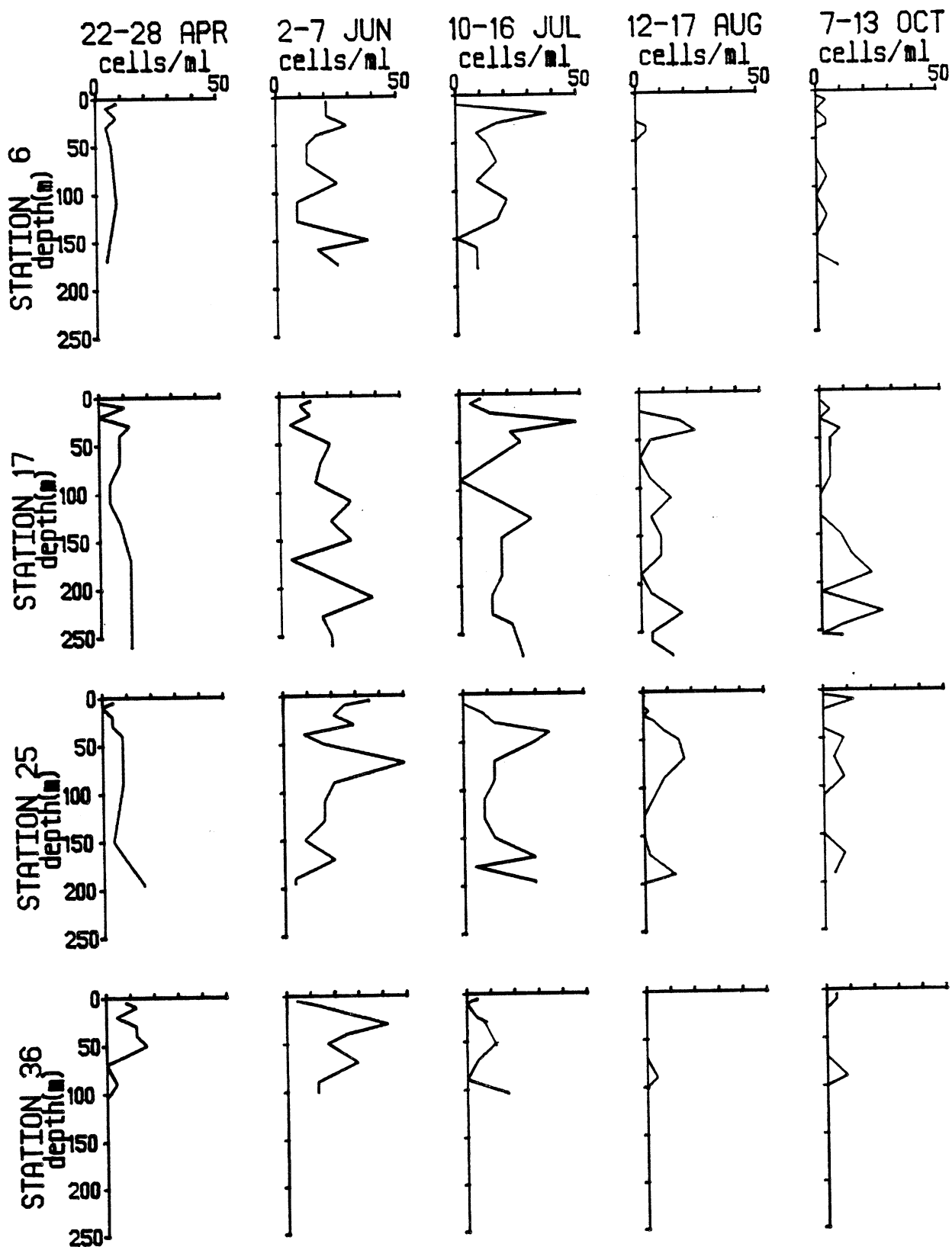


FIG. 106. Vertical distribution of *Scenedesmus bicellularis*.

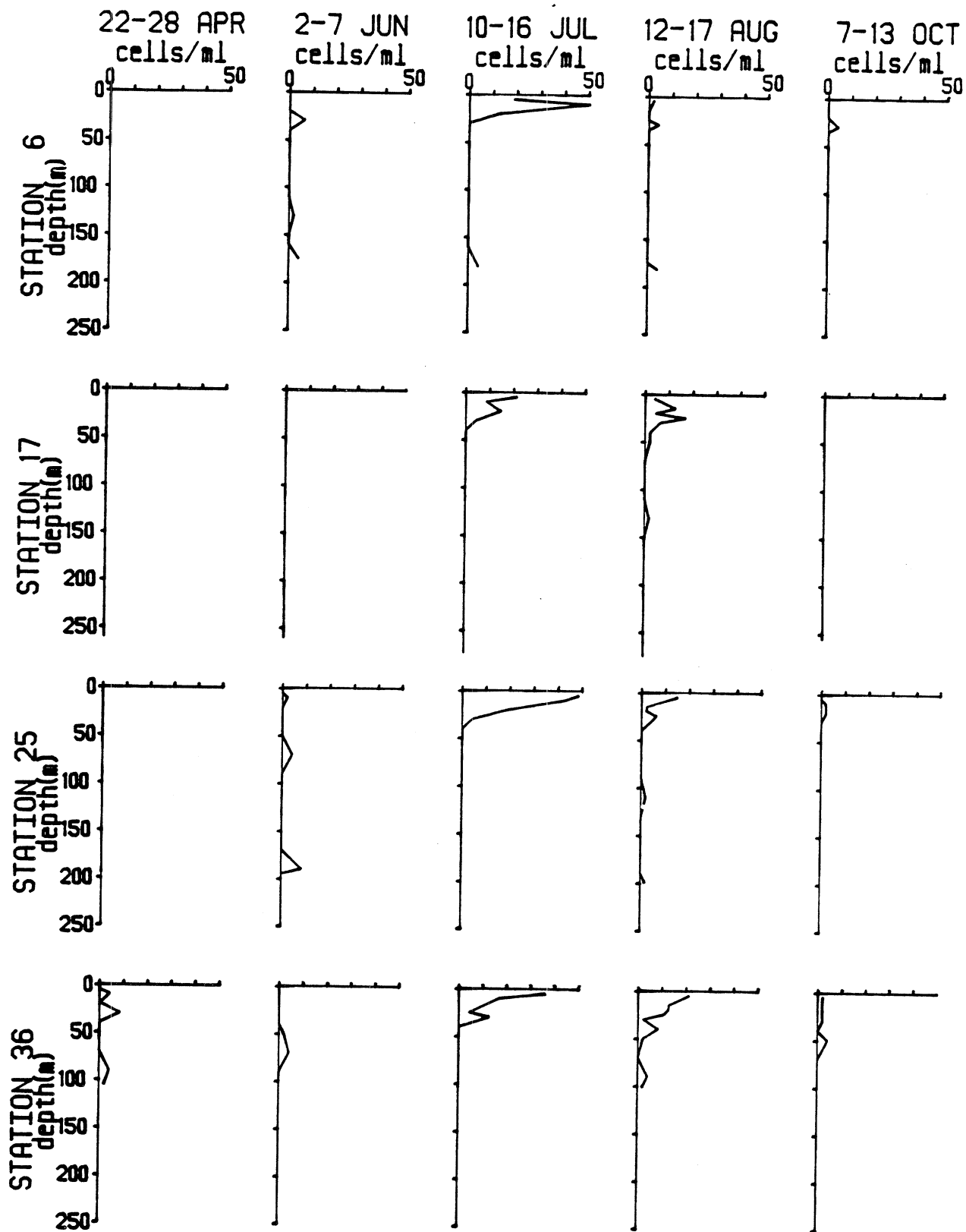


FIG. 107. Vertical distribution of *Ankistrodesmus* sp. #6.

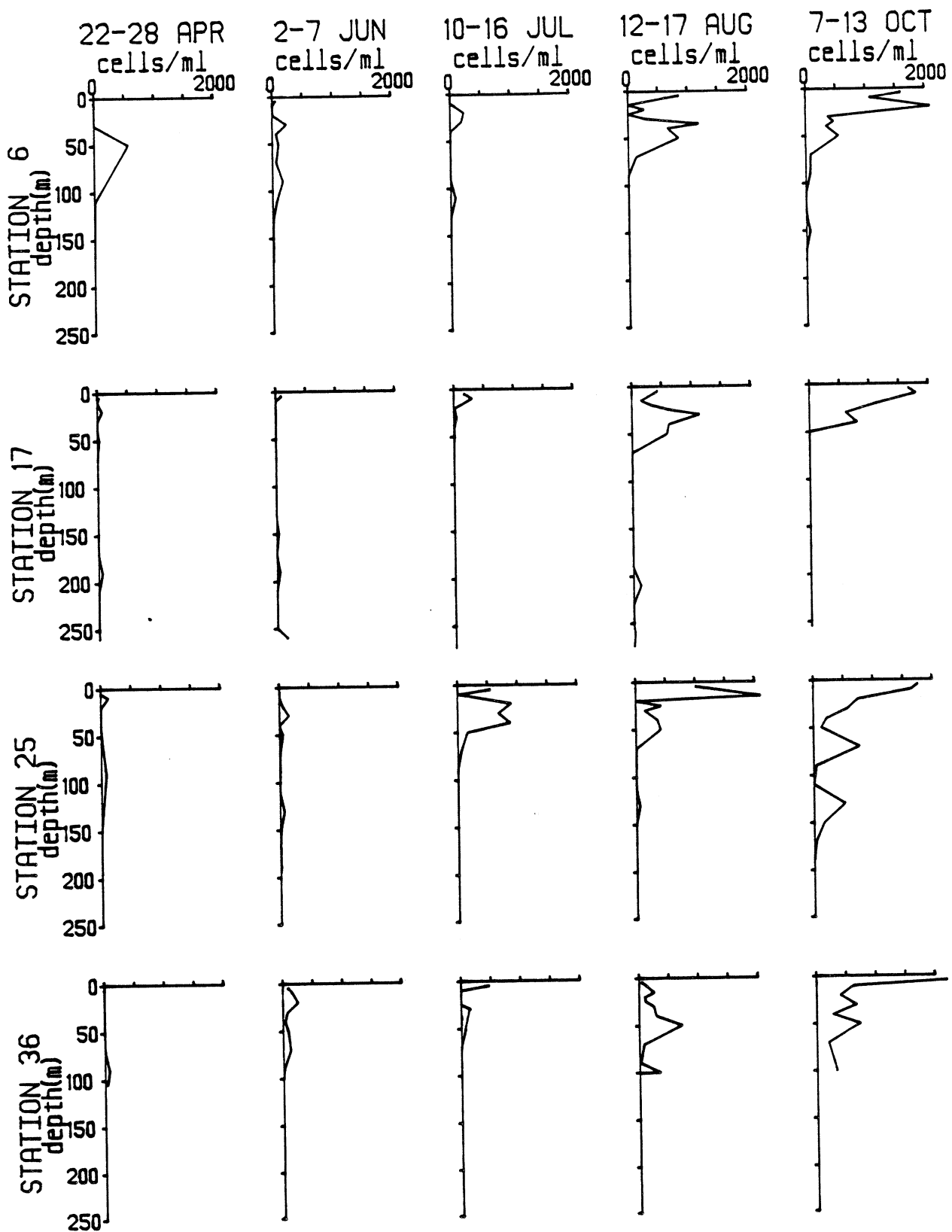


FIG. 108. Vertical distribution of blue-green algae.

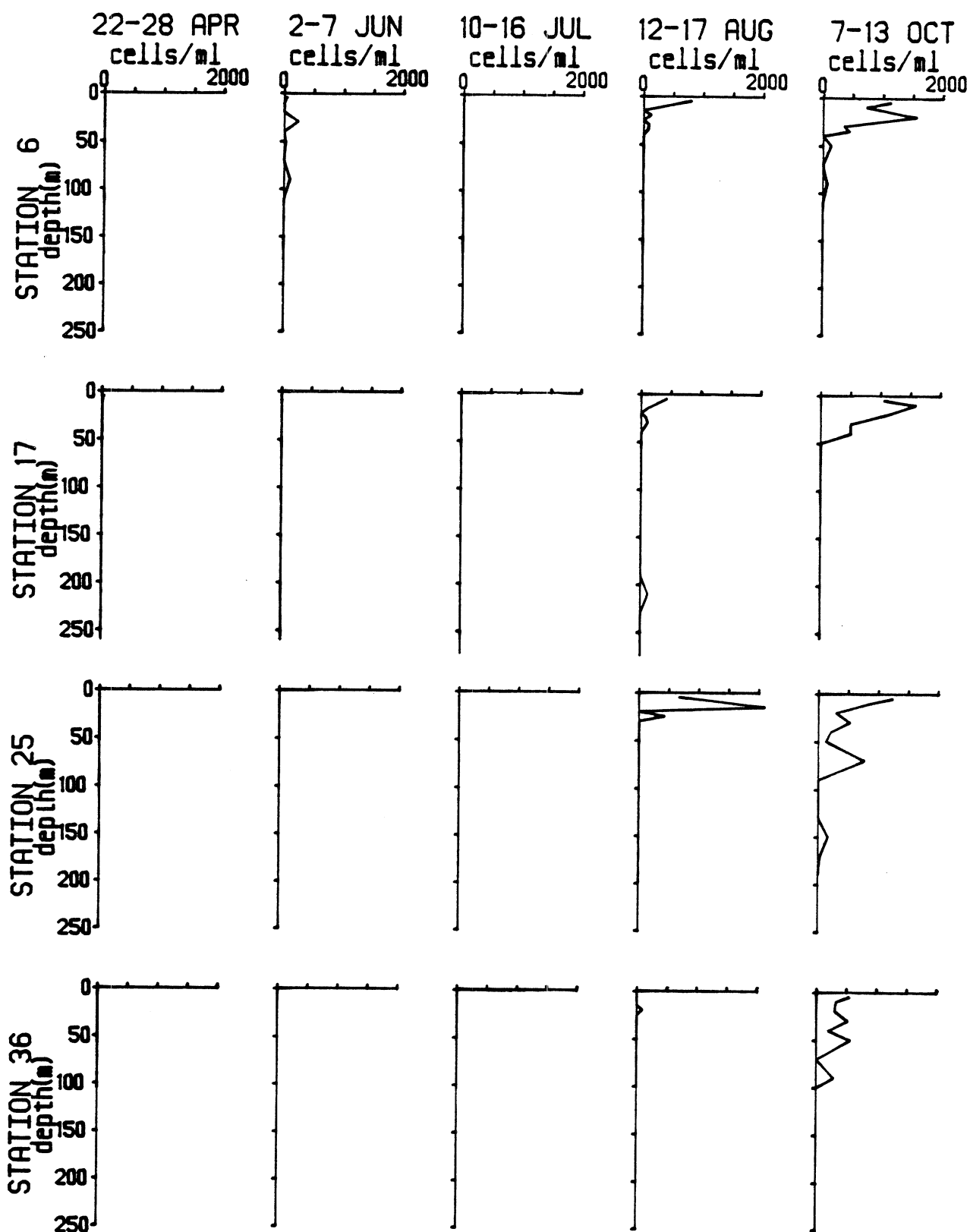


FIG. 109. Vertical distribution of Anacystis incerta.

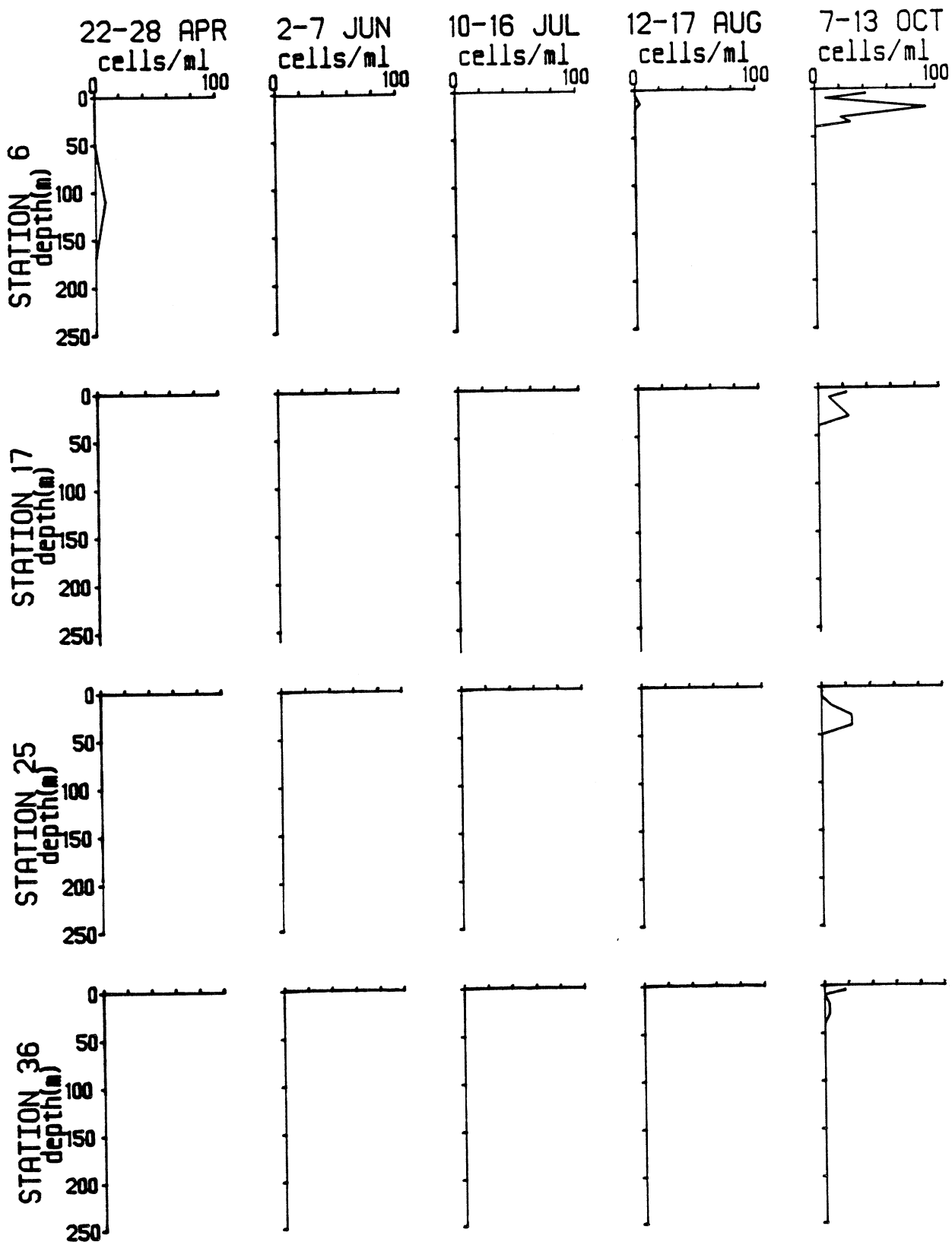


FIG. 110. Vertical distribution of *Anacystis thermalis*.

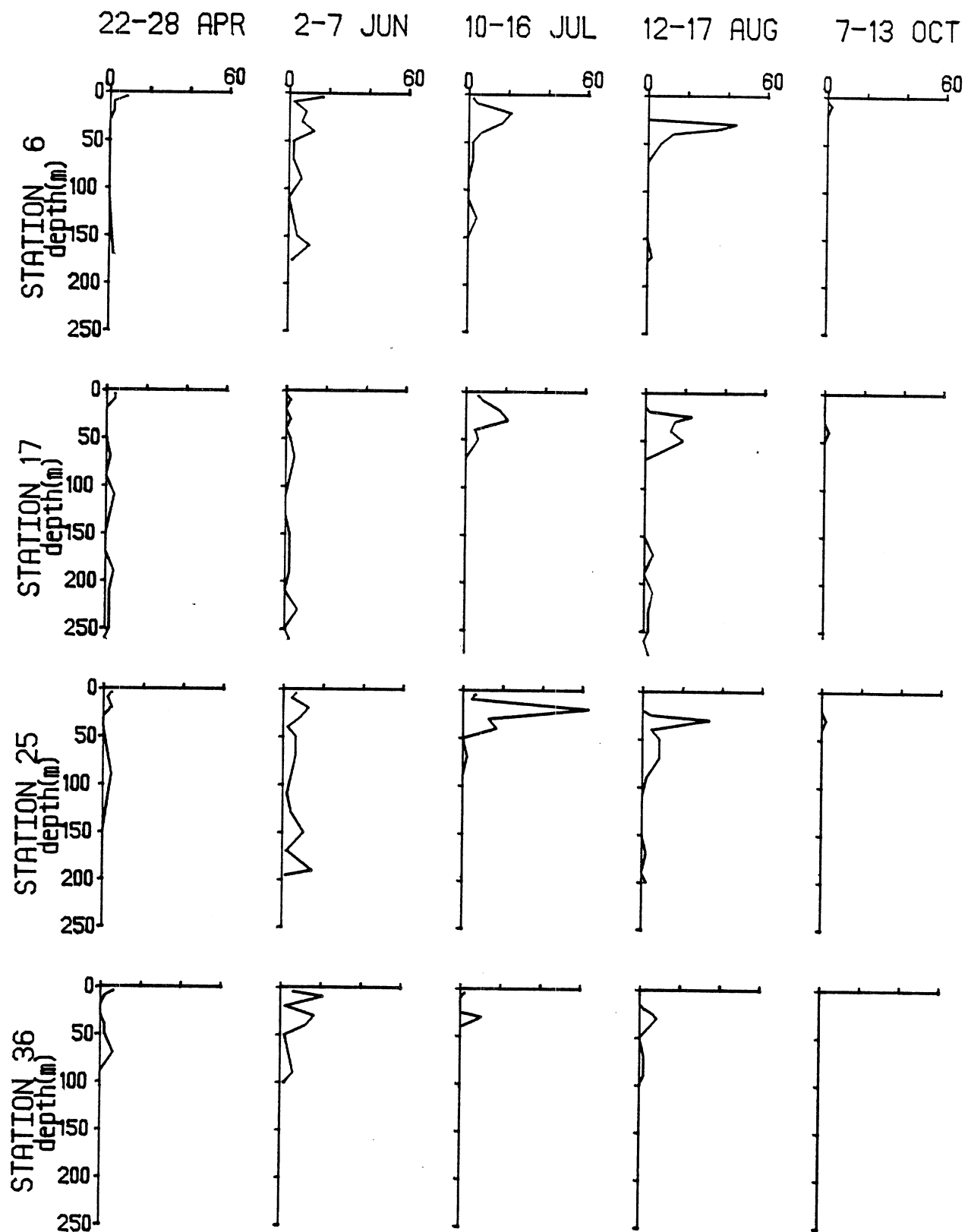


FIG. 111. Vertical distribution of Schizothrix calcicola (filaments/mL).

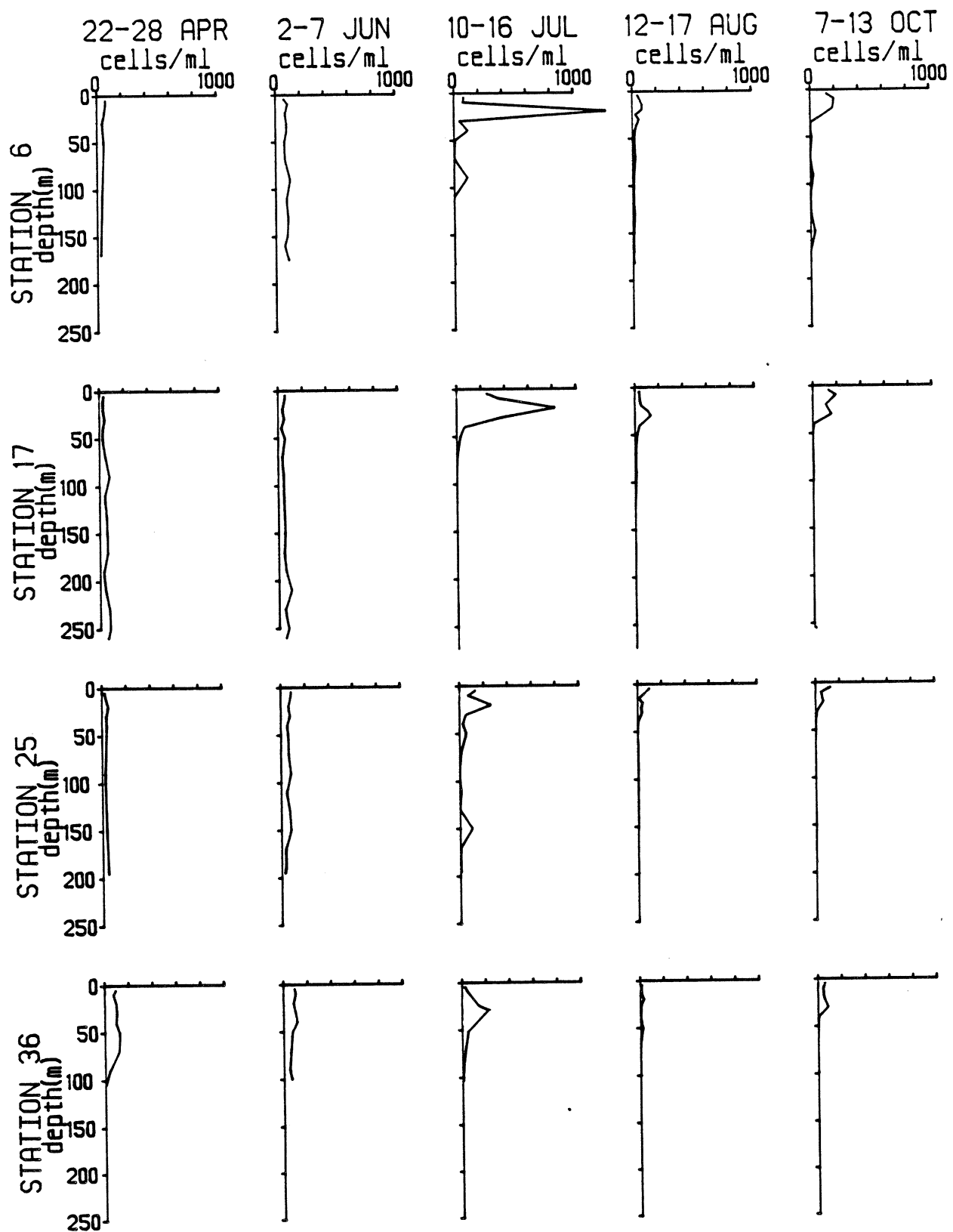


FIG. 112. Vertical distribution of chrysophytes.

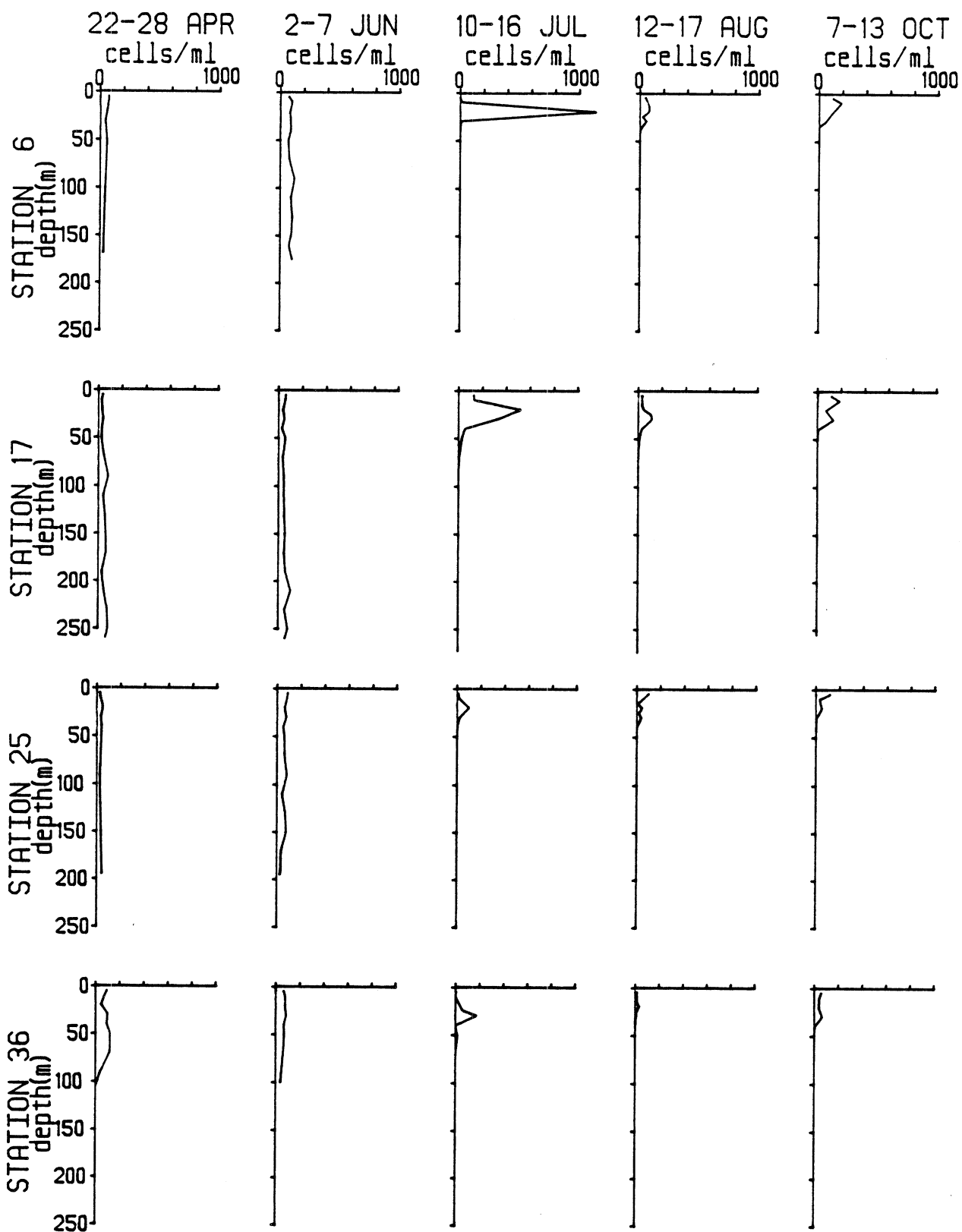


FIG. 113. Vertical distribution of the genus *Ochromonas*.

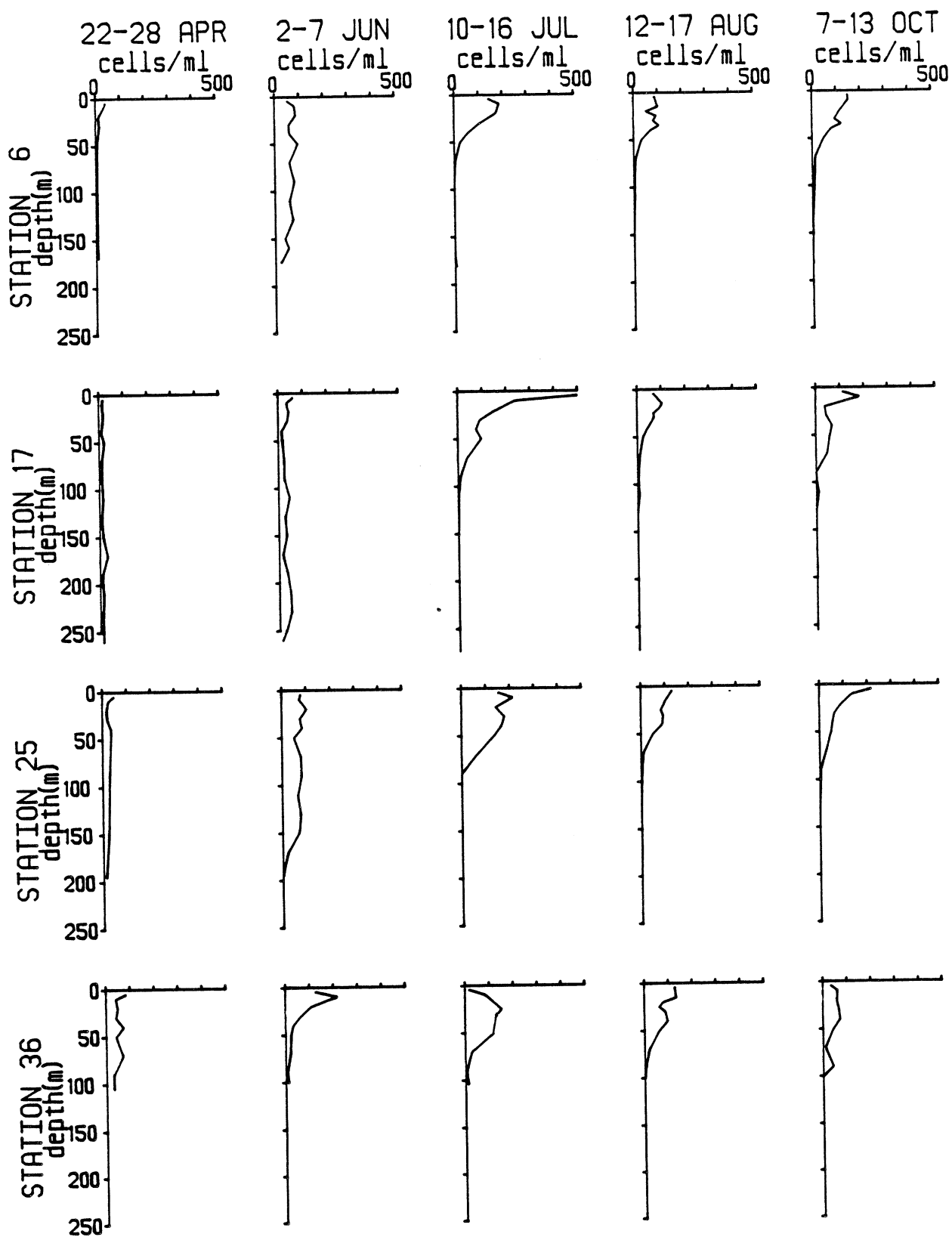


FIG. 114. Vertical distribution of cryptomonads.

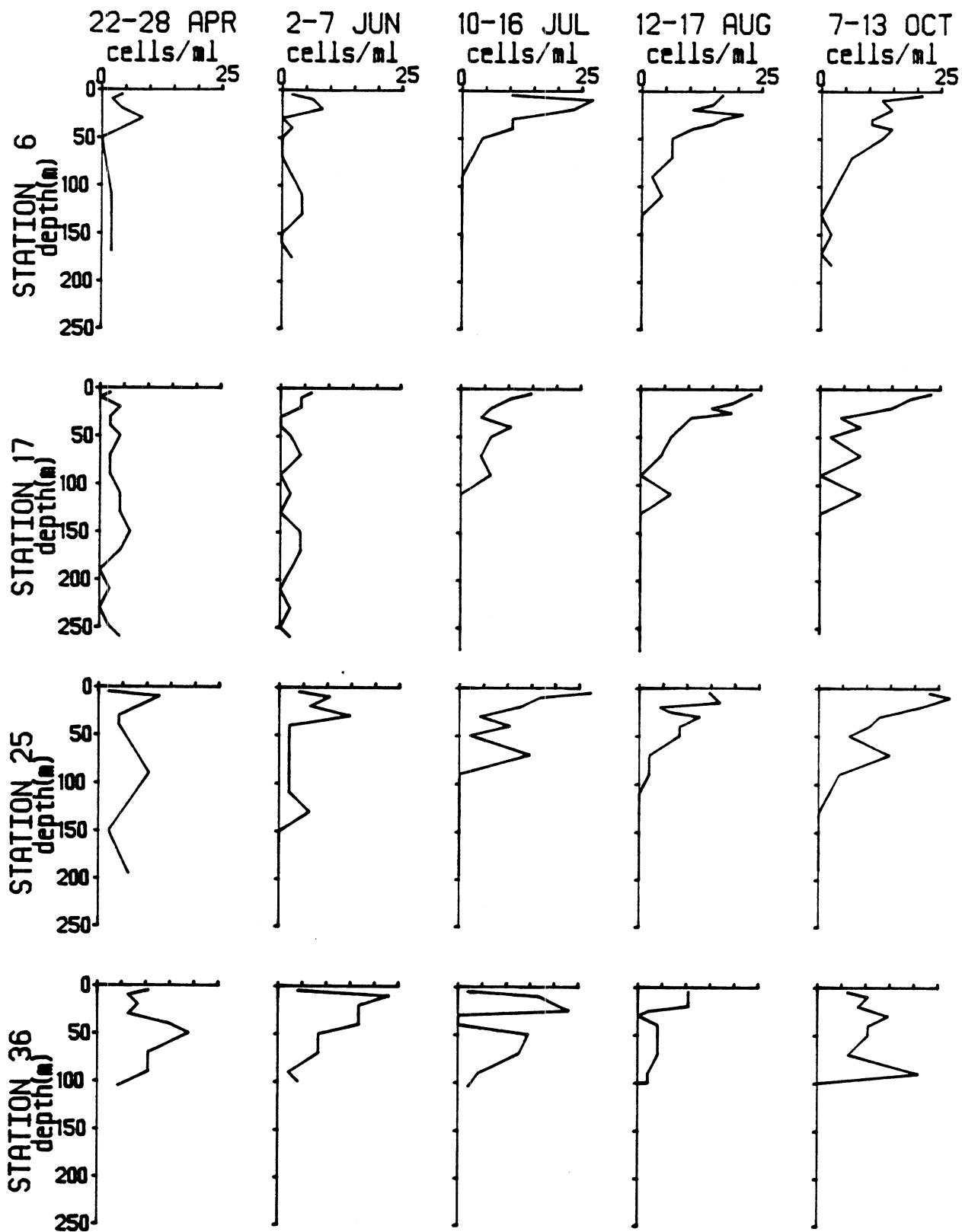


FIG. 115. Vertical distribution of the genus Cryptomonas.

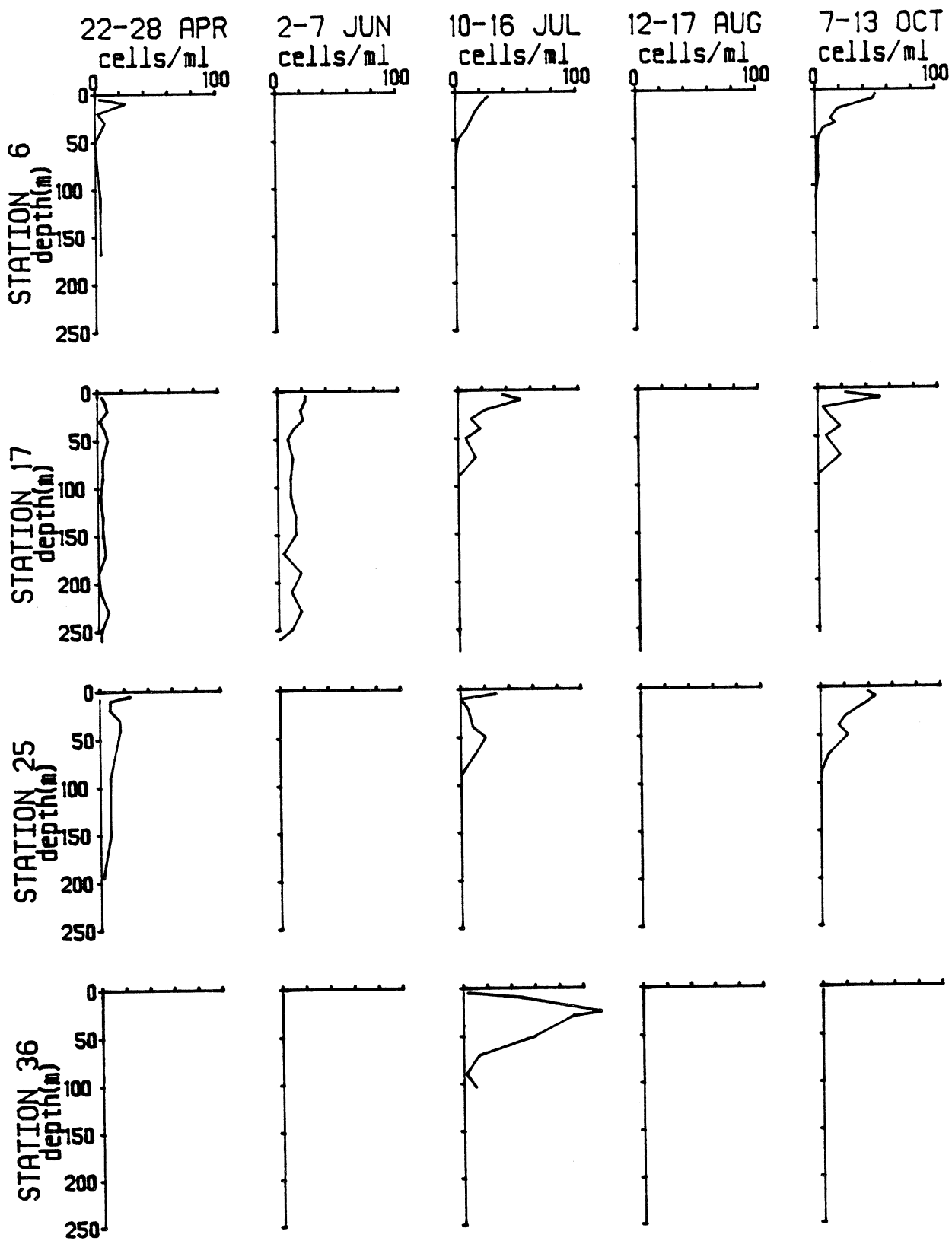


FIG. 116. Vertical distribution of *Rhodomonas minuta*.

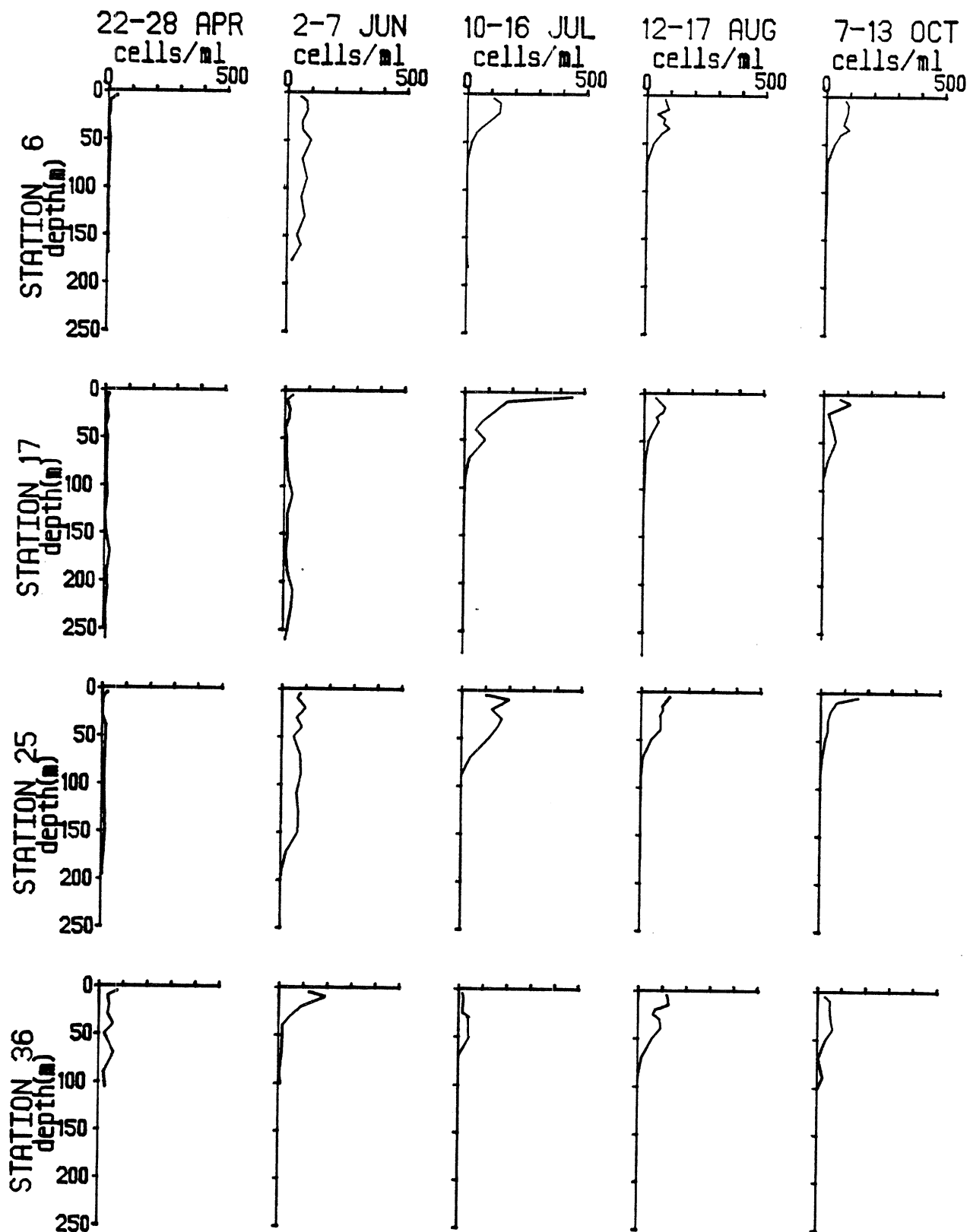


FIG. 117. Vertical distribution of *Rhodomonas minuta* var. *nannoplanctica*.

Due to their relative rarity, the vertical distribution of dinoflagellates was rather erratic (Fig. 118). Highest abundance was found in subthermocline maxima developed in July.

The vertical distribution of unidentified small flagellates (Fig. 119) was somewhat similar to that of the Cryptomonads except that there was a tendency to develop dual peaks in abundance near the surface and at or below thermocline depth, particularly in July. This may represent the fact that several populations were present in this composite group, which have different distribution patterns.

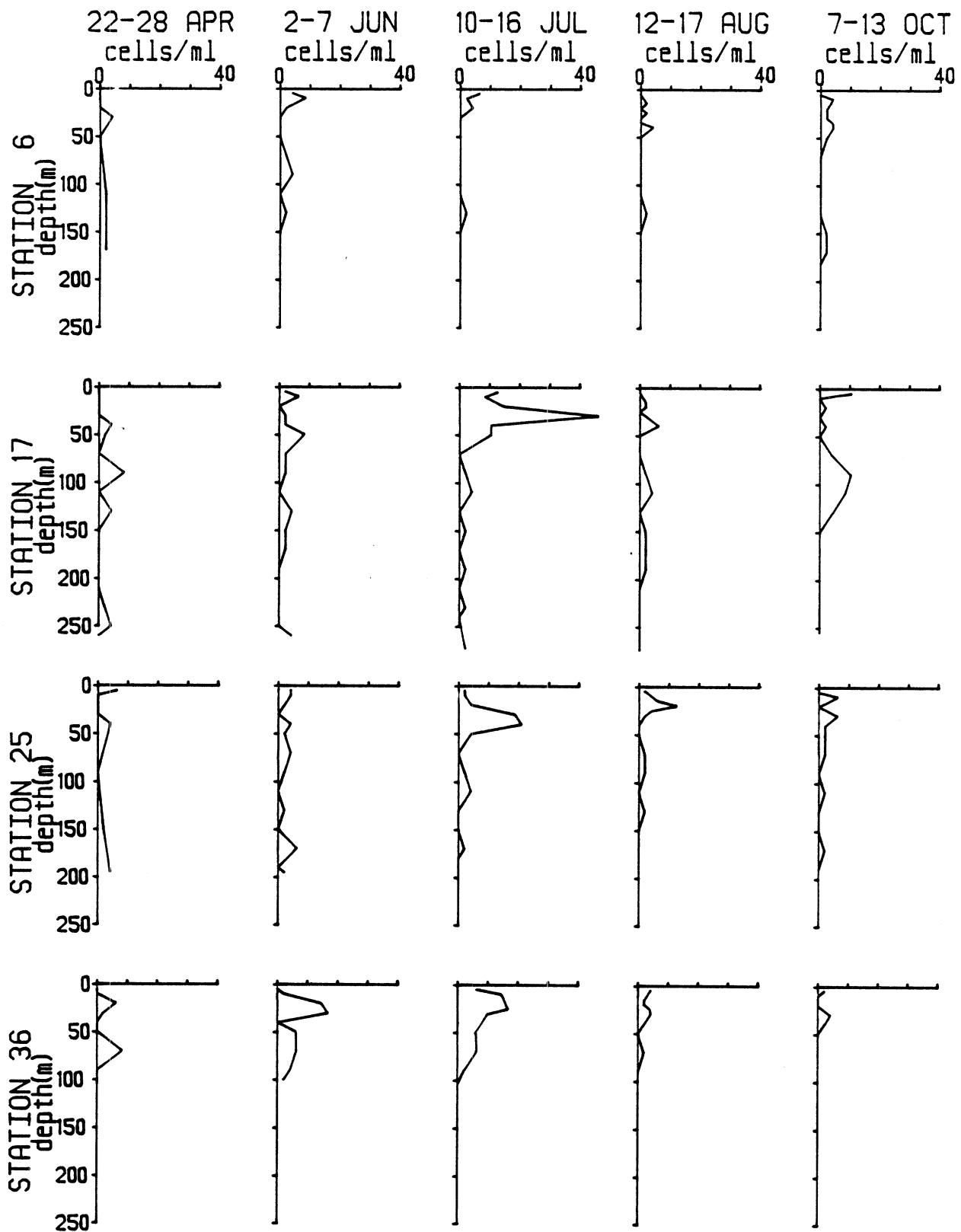


FIG. 118. Vertical distribution of dinoflagellates.

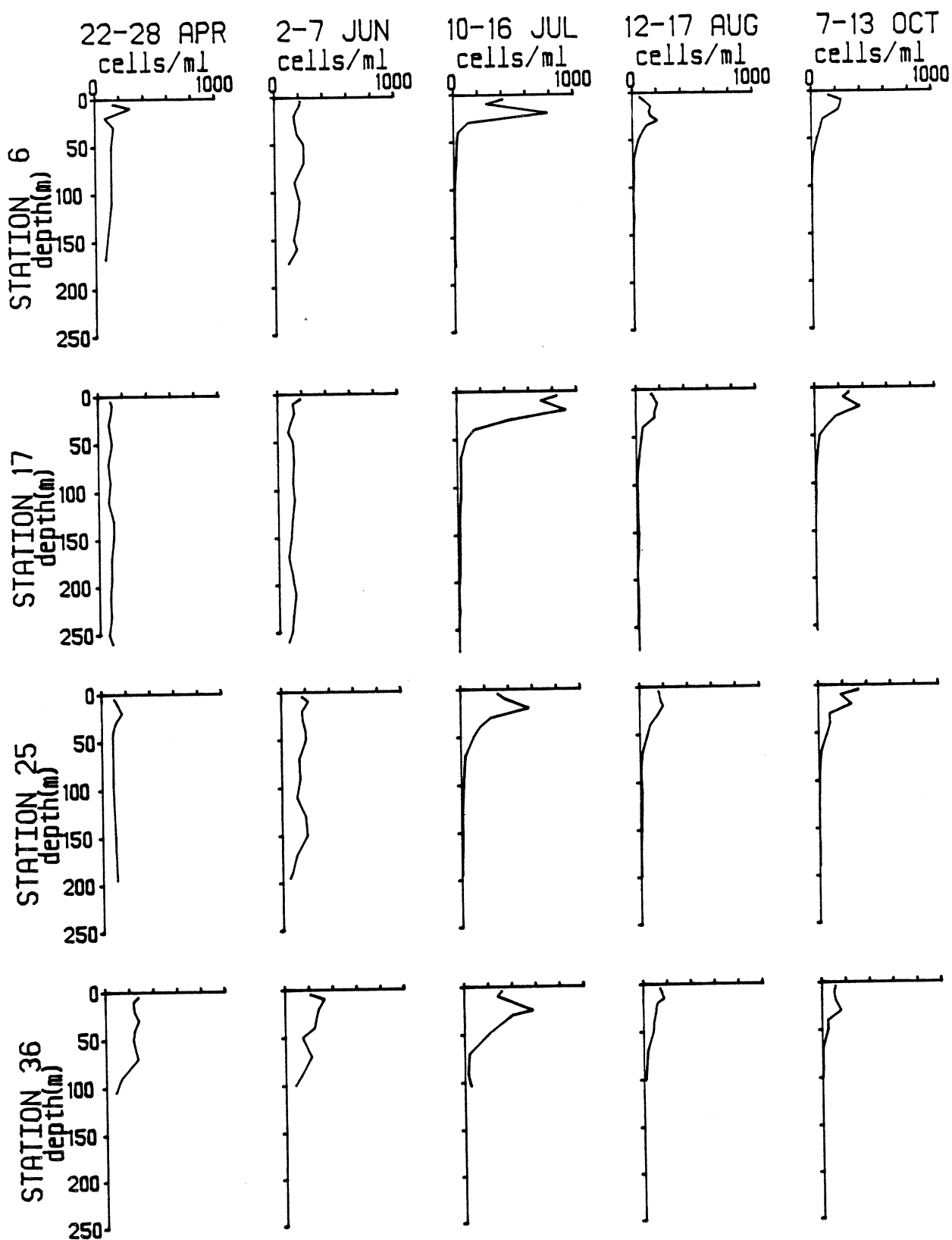


FIG. 119. Vertical distribution of unidentified flagellates.

DISCUSSION AND CONCLUSIONS

The general pattern of phytoplankton distribution in the surface waters of northern Lake Michigan shows several effects of the different physical provinces present and different loading conditions imposed by both natural and modified conditions. Areas of specific effects attributable to anthropogenic loadings are not extensive. Samples from the Rawley Point area consistently show high population densities and the presence of populations usually associated with degraded water quality. The source of this influence is not entirely clear from our data, but it is probably that this region is differentiated by a combination of loadings from the Manitowoc, Wisconsin, region and periodic nutrient resupply from upwelling after stratification. The same situation occurs, to a somewhat more limited extent, on the eastern side of the lake in the Big Sable Point region. The effects in this region are not so consistent nor so extensive, but there is evidence of direct effects of shoreline point source loadings affecting phytoplankton composition and abundance. Somewhat surprisingly, the stations which could be affected by loadings from Green Bay show more diffuse and integrated effects. Stations near Sturgeon Bay and Death's Door showed an increase in phytoplankton abundance during certain sampling periods, and an increase in eurytopic taxa tolerant of increased nutrient loads. Samples from these stations do not, however, contain large populations of species associated with very high point source loadings. This more integrated type of effect appears to be consistent with Stoermer and Stevenson's (1980) study of phytoplankton distribution in Green Bay. Their results indicate that the phytoplankton flora of northern Green Bay is influenced extensively by loadings from the southern bay and by

exchange from open Lake Michigan, resulting in a flora which is more or less intermediate in composition and abundance. The effects of loadings to Green Bay are thus "processed" within Green Bay and floristic modifications are not as great as those which result from direct loadings.

It is clear that the Straits region of northern Lake Michigan is quite distinct from the rest of the lake in terms of phytoplankton species composition, abundance, and seasonal cycle. This region appears to be an example of naturally productive areas within the system which have not been severely modified. The region maintains relatively high levels of phytoplankton standing crop, but many of the species present are those which do not tolerate eutrophication. In this respect, the Straits region is perhaps the best analog of conditions in Lake Michigan before the system was modified by anthropogenic impacts. Silica supplies are periodically replenished during summer stratification, which allows certain indigenous populations, which have been largely extirpated from the rest of the lake, to exist in significant numbers in this region. Both abundance and composition of phytoplankton in this region tend to be more stable than in the rest of northern Lake Michigan. One other characteristic of the Straits region is the relatively high abundance of species which are obviously derived from benthic communities in the plankton samples. Although this has seldom been discussed in the literature, certain regions of the Great Lakes commonly have relatively large concentrations of benthic algae entrained in the plankton. Although these species are not as numerically abundant as the euplanktonic populations, they may constitute an appreciable fraction of the biomass because of the large size of some benthic species. In northern Lake Michigan, with the exception of the Straits area, most significant occurrences of benthic algae

in the phytoplankton collections are found at nearshore stations. Exceptionally high values were found at Station 67 in the July sample, but this pattern was not repeated in subsequent sampling periods and the reason for this particular anomalous occurrence is not apparent.

Some examples of atypical distribution patterns or occurrences were noted during the study. These are of particular interest because they may signal early stages of modification of the system. As an example, Cyclotella comensis was present at most stations sampled during this study. On the basis of available records, this species has not been an important component of phytoplankton assemblages in Lake Michigan previously. This species has generally been reported from oligotrophic lakes, and seems to be increasing in abundance in the Great Lakes. It is now a major dominant in Lake Huron (Stoermer and Kreis 1980). On the basis of Stoermer and Kreis's data, this taxon appears to be particularly efficient at silica utilization, but has a high nitrate requirement. In Lake Michigan, it is most abundant in the Straits area, where these requirements would be met by nutrient replenishment from the hypolimnion. It has, however, also been able to invade stations in the open lake despite very low ambient silica levels which effectively limit the growth of other diatoms. Occurrences of Cyclotella pseudostelligera are usually associated with very high nutrient loadings. The unusual abundance of this species at stations in the Rawley Point vicinity thus may be taken as an indication of atypical loadings in this vicinity. This is further supported by the abundance of other extremely eutrophication-tolerant species, such as Stephanodiscus subtilis and atypically high total phytoplankton abundance at the same stations. Other eutrophication-tolerant species were much more abundant in our samples than in previous studies. Scenedesmus bicellularis

was abundant at stations sampled early in the season. This species is a major numerical dominant in Lake Erie and Lake Ontario, but has not been previously reported as abundant in Lake Michigan. The extreme abundance of a small, filamentous, green alga of uncertain taxonomic affinities (designated as green filament sp. #5) is particularly noteworthy. This taxon is a dominant in extremely eutrophic regions of the Great Lakes system, such as Saginaw Bay (Stoermer and Kreis 1980). Its distribution in Lake Michigan is highly unusual. It forms a pronounced deep maximum, particularly at Station 6, during summer stratification. Its seasonal occurrence is apparently limited, as few occurrences were noted in the surface waters, either before or after the establishment of stratification.

Although such specific effects are apparent in the phytoplankton distribution data, perhaps the most interesting aspect of our results is the subtle, long-term modification of the phytoplankton flora in the northern Lake Michigan region which has resulted from the integrated effects of increased loading to the system. This is especially apparent in northern Lake Michigan because the rather special physical conditions in the Straits region result in retention of a flora in this region which is more similar to the indigenous type.

One of the striking aspects of the present-day phytoplankton flora is the extreme depth segregation of populations during the summer stratification. Many populations, particularly those associated with oligotrophic habits, are substantially excluded from the surface waters during stratification. Our data indicate that many of these populations survive at sub-thermocline depths during the stratified period. They are replaced in the surface waters by populations which are tolerant of silica limitation, particularly blue-green

algae and flagellates. It is particularly interesting to note that most of these populations do not apparently survive sinking to any appreciable extent. Thus nutrients sequestered in them are recycled to a greater extent than those sequestered by indigenous populations. This may prove important in evaluating the future response of this segment of the Lake Michigan system to future loadings. One of the factors which has resulted in extreme modification of the production base of highly eutrophied systems, such as Lake Ontario, is an increase in epilimnetic populations during the summer to the point that indigenous populations can no longer exist in the sub-thermocline "refugium" because of shading. At this point, production and nutrient sequestering is restricted to the epilimnion, resulting in even higher total phytoplankton densities, particularly of less desirable populations. Our data indicate that this mechanism, once initiated, may be self-perpetuating to a certain extent. Increased loadings result in increased abundance of rapidly growing, thermal-tolerant populations in the epilimnion which act as a partial nutrient trap due to rapid recycle. In such a situation relatively modest further increases in nutrient loading could result in a major shift toward complete dominance by this component of the phytoplankton assemblage and a drastic modification of the production base and apparent water quality in the region.

Our results thus indicate that northern Lake Michigan is poised at a rather critical state. The paucity of previous comprehensive data from this region makes definition of trends within the system somewhat hazardous. The apparent increasing abundance of green and blue-green algal populations, increased abundance of these populations early in the year, and their invasion of the deep phytoplankton maximum may be taken as indicative of drift toward a less desirable condition. On the other hand, there are indications of

reduction in the abundance of certain populations which are particularly responsive to direct nutrient loading. Populations such as Stephanodiscus binderanus which have been widely associated with water quality problems in Lake Michigan have apparently declined compared to levels noted in previous studies (Stoermer and Yang 1970).

REFERENCES

- Ahlstrom, E. H. 1936. The deep-water plankton of Lake Michigan, exclusive of the crustacea. *Trans. Amer. Microsc. Soc.* 55: 286-299.
- Hohn, M. H. 1969. Qualitative and quantitative analyses of plankton diatoms, Bass Island area, Lake Erie, 1938-1965, including synoptic surveys of 1960-1963. *Ohio Biol. Surv., N.S., Vol. 3, No. 1.* 211 pp.
- Hutchinson, G. E. 1967. A treatise on limnology. II. Introduction to lake biology and the limnoplankton. Wiley, New York. 1,115 pp.
- Schelske, C. L., and E. F. Stoermer. 1971. Eutrophication, silica and predicted changes in algal quality in Lake Michigan. *Science* 173: 423-424.
- _____, and E. F. Stoermer. 1972. Phosphorus, silica and eutrophication of Lake Michigan, pp. 157-171. *In* G. E. Likens (ed.), *Nutrients and eutrophication, Special Symposia Vol. 1*, Amer. Soc. Limnol. Oceanogr., Allen Press, Lawrence, Kansas.
- _____, L. E. Feldt, M. A. Santiago, and E. F. Stoermer. 1972. Nutrient enrichment and its effect on phytoplankton production and species composition in Lake Superior, pp. 149-165. *In* *Proc. 15th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res.*
- _____, E. F. Stoermer, J. E. Gannon, and M. S. Simmons. 1976. Biological, chemical and physical relationships in the Straits of Mackinac. *Ecol. Res. Series*, U.S. Environmental Protection Agency, Duluth, Minnesota, Rep. No. EPA-600/3-76-095. 266 pp.
- Stoermer, E. F. 1978. Phytoplankton as indicators of water quality in the Laurentian Great Lakes. *Trans. Amer. Microsc. Soc.* 97: 2-16.
- _____. 1979. Bloom and crash: algae in the lakes. Chapter 2, pp. 13-20. *In* J. Rousmaniere (ed.), *The enduring Great Lakes*. W. W. Norton & Company, New York.
- _____, and R. G. Kreis, Jr. 1980. Phytoplankton composition and abundance in southern Lake Huron. *Univ. Michigan, Great Lakes Res. Div., Spec. Rep.* 65. 382 pp.
- _____, and R. J. Stevenson. 1980. Green Bay phytoplankton composition, abundance and distribution. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, Illinois, Rep. No. EPA-905/3-79-002. 88 pp.
- _____, and J. J. Yang. 1969. Plankton diatom assemblages in Lake Michigan. *Univ. Michigan, Great Lakes Res. Div., Spec. Rep.* 47. 168 pp.

- _____, and J. J. Yang. 1970. Distribution and relative abundance of dominant plankton diatoms in Lake Michigan. Univ. Michigan, Great Lakes Res. Div., Publ. 16. 64 pp.
- _____, M. M. Bowman, J. C. Kingston, and A. L. Schaedel. 1974. Phytoplankton composition and abundance in Lake Ontario during IFYGL. Univ. Michigan, Great Lakes Res. Div., Spec. Rep. 53. 373 pp.
- _____, R. G. Kreis, Jr., and L. Sicko-Goad. 1981. A systematic, quantitative, and ecological comparison of Melosira islandica O. Müll. with M. granulata (Ehr.) Ralfs from the Laurentian Great Lakes. J. Great Lakes Res. 7: 345-356.
- Uherkovich, G. 1966. Die Scenedesmus-Arten Ungarns. Akadémiai Kiadó, Budapest. 173 pp.
- Vollenweider, R. A., M. Munawar, and P. Stadelmann. 1974. A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. J. Fish. Res. Board Can. 31: 739-762.

APPENDIX I.

Following is a summary of phytoplankton occurrence and abundance in northern Lake Michigan. Populations are listed alphabetically by major group. The first column gives the Latin name, or other designation in cases of populations which could not be clearly identified. The second column gives the total number of occurrences within the number of samples examined. Column three gives the average population density ($\text{cells}^1 \cdot \text{mL}^{-1}$) for the number of occurrences. Column four gives the average relative abundance of the population in the total assemblage where it occurs. Column five gives the maximum observed population density ($\text{cells}^1 \cdot \text{mL}^{-1}$) and column six gives the maximum observed relative abundance of each population. Column seven indicates the sample number containing the greatest observed population density and the "F#" following indicates the data file within this project where this information is stored. The final two columns display the same information for relative frequency data. The final statement (p. 245) gives the total number of samples observed, the total number of taxa observed, the maximum and minimum assemblage abundances ($\text{cells}^1 \cdot \text{mL}^{-1}$) and the sample numbers where these values were found, and the average total assemblage abundance averaged over all samples analyzed.

SUMMARY OF PHYTOPLANKTON SPECIES ABUNDANCE

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide F# | max % pop. slide F# | taxon code |
|--|------------------|-----------------------------|-----------------------------|-------------------------|------------------------|---------------|
| Undetermined colony sp. #1. | 22 | 8.764 | 1466.075 | 3027 | 2 | UCSPECOA |
| Undetermined colony sp. #2. | 245 | 18.371 | 192.684 | 2744 | 1 | UCSPECOB |
| Undetermined cyst | 4 | 0.116 | 33.510 | 4380 | 5 | CXSTSPEQ |
| Undetermined flagellate spp. | 524 | 192.128 | 1352.978 | 2977 | 2 | FLSPP |
| total undetermined (4 categories) | | 219.379 | 13.168 | | | |

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide F# | max % pop. slide F# | taxon code |
|---|------------------|-----------------------------|-----------------------------|-------------------------|------------------------|---------------|
| Anabaena flos-aquae | 92 | 33.541 | 3801.324 | 3318 | 3 | ABFLOSAQ |
| Anabaena sp. | 9 | 2.176 | 831.474 | 3812 | 6 | ABSP |
| Anabaena spp. | 1 | 0.035 | 18.850 | 3754 | 8 | ABSP |
| Anabaena subcylindrica. | 14 | 4.768 | 875.457 | 3741 | 8 | ABSUBCYL |
| Anacystis cyanea. | 2 | 0.595 | 314.159 | 3639 | 4 | AYCYANEA |
| Anacystis incerta | 135 | 173.785 | 5116.602 | 3661 | 4 | AYINCERT |
| Anacystis thermalis | 99 | 4.567 | 92.153 | 4626 | 6 | AYTHERMA |
| Beggiatoa sp. | 6 | 0.773 | 113.097 | 3813 | 6 | BESP |
| Coccolithus elabens. | 1 | 0.019 | 10.472 | 2794 | 1 | CCELAREN |
| Coccolithus stagnina | 5 | 2.330 | 733.038 | 4376 | 5 | CCSTAGNI |
| Dactylococopsis acicularis | 43 | 0.424 | 27.227 | 3342 | 8 | DACICUL |
| Dactylococopsis raphidioides. | 14 | 0.402 | 27.227 | 2961 | 9 | DARHAPHI |
| Dactylococopsis sp. | 1 | 0.062 | 33.510 | 3687 | 7 | DASP |
| Gomphosphaeria aponina. | 3 | 0.162 | 33.510 | 4514 | 5 | GAPONIN |
| Gomphosphaeria lacustris. | 61 | 43.511 | 1361.356 | 4630 | 6 | GNLACUST |
| Gomphosphaeria sp. | 1 | 0.004 | 2.094 | 3156 | 3 | GNSP |
| Gomphosphaeria spp. | 2 | 0.240 | 125.664 | 3416 | 3 | GNSP |
| Gomphosphaeria wichurae | 77 | 48.905 | 1466.075 | 4417 | 7 | GNWICHUR |
| Microcoleus vaginatus | 81 | 26.454 | 918.908 | 2881 | 2 | MBVAGINA |
| Oscillatoria bornetii | 7 | 1.039 | 140.324 | 4420 | 5 | OSBORNET |
| Oscillatoria limnetica. | 6 | 0.707 | 159.174 | 2734 | 1 | OSLINNET |
| Oscillatoria retzii | 32 | 11.156 | 867.079 | 3293 | 7 | OSRETZII |
| Oscillatoria sp. | 2 | 0.193 | 73.304 | 3013 | 7 | OSSP |
| Oscillatoria tenuis | 2 | 0.282 | 100.531 | 2695 | 1 | OSTENUIS |
| Oscillatoria tenuis var. tergestina | 33 | 5.468 | 339.292 | 4629 | 6 | OSTENUVT |
| Schizothrix calcicola | 247 | 3.644 | 62.832 | 3121 | 2 | SZCALCIC |
| Undetermined blue-green colony. | 1 | 0.073 | 39.793 | 2750 | 1 | BGCOL |

| Undetermined blue-green filament. (28 categories) | | | | | | | | | | BGPIL | | | |
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| total blue-green | | | | | | | | | | 2963 9 | | | |
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| Kirchneriella contorta. | 12 | 0.143 | 0.012 | 16.755 | 1.961 | 2601 | 1 | 4561 | 8 | KICONTOR |
| Kirchneriella elongata. | 2 | 0.023 | 0.001 | 8.378 | 0.320 | 3018 | 2 | 3018 | 2 | KIELONGA |
| Kirchneriella sp. | 2 | 0.008 | 0.001 | 2.094 | 0.373 | 3072 | 2 | 3819 | 6 | KISP |
| Kirchneriella subsolitaria. | 4 | 0.046 | 0.002 | 8.378 | 0.351 | 3080 | 2 | 3205 | 3 | KISUBSOL |
| Lagerheimia genevensis. | 2 | 0.027 | 0.001 | 12.566 | 0.206 | 3077 | 2 | 3077 | 2 | LACENEVE |
| Lagerheimia subsalsa. | 1 | 0.004 | 0.000 | 2.094 | 0.066 | 4423 | 5 | 4423 | 5 | LASSALSA |
| Lobocystis dichotoma. | 1 | 0.023 | 0.002 | 12.566 | 0.840 | 3172 | 3 | 3172 | 3 | LODICHOT |
| Mougeotia sp. | 36 | 0.522 | 0.035 | 29.322 | 2.564 | 2794 | 1 | 4461 | 9 | MOSP |
| Mougeotia spp. | 23 | 0.595 | 0.035 | 50.265 | 2.895 | 2871 | 2 | 2871 | 2 | MOSPP |
| Nephrocystium aqardhianum. | 91 | 11.488 | 0.645 | 454.483 | 32.278 | 3598 | 4 | 3500 | 4 | NPAGARDH |
| Nephrocystium limnaticum | 2 | 0.058 | 0.004 | 16.755 | 1.044 | 3368 | 3 | 3368 | 3 | NPLIMNET |
| Nephrocystium lunatum. | 5 | 0.100 | 0.005 | 25.133 | 1.581 | 3271 | 3 | 3271 | 3 | NPLUNATO |
| Nephrocystium spp. | 1 | 0.093 | 0.002 | 50.265 | 1.163 | 3579 | 4 | 3579 | 4 | NPSP |
| Nephrocystium spp. | 3 | 1.333 | 0.130 | 322.537 | 38.596 | 3518 | 4 | 3518 | 4 | NPSP |
| Oedogonium spp. | 1 | 0.019 | 0.000 | 10.472 | 0.229 | 2647 | 1 | 2647 | 1 | ODSP |
| Oocystis borgeri | 1 | 0.386 | 0.023 | 209.439 | 12.632 | 2823 | 1 | 2823 | 1 | OBOBORGERI |
| Oocystis parva. | 2 | 0.019 | 0.001 | 8.378 | 0.183 | 2647 | 1 | 2647 | 1 | OOPARVA |
| Oocystis pusilla ?. | 84 | 17.968 | 0.663 | 846.135 | 29.402 | 3577 | 4 | 3588 | 4 | OOPUSILQ |
| Oocystis sp. | 52 | 1.001 | 0.086 | 71.209 | 6.154 | 4583 | 5 | 4634 | 6 | OOSP |
| Oocystis spp. | 191 | 11.975 | 0.658 | 152.891 | 17.340 | 3628 | 9 | 3628 | 9 | OOSPP |
| Pediastrum boryanum | 1 | 0.100 | 0.006 | 54.454 | 3.490 | 2964 | 9 | 2964 | 9 | PDBORYAN |
| Pediastrum tetras | 1 | 0.031 | 0.001 | 16.755 | 0.339 | 4599 | 5 | 4599 | 5 | PDTETRAS |
| Phacotus lenticularis | 1 | 0.004 | 0.002 | 2.094 | 0.820 | 4635 | 6 | 4635 | 6 | PCLENTIC |
| Planctonema lauterbornii. | 2 | 0.058 | 0.003 | 23.038 | 1.419 | 3836 | 4 | 3836 | 4 | PMLAUTER |
| Quadriqla chodatii | 2 | 0.031 | 0.001 | 8.378 | 0.403 | 3189 | 3 | 3189 | 3 | QUCHODAT |
| Quadriqla lacustris. | 7 | 0.158 | 0.008 | 16.755 | 1.346 | 3737 | 4 | 3738 | 8 | QLACUST |
| Quadriqla spp. | 1 | 0.015 | 0.001 | 8.378 | 0.459 | 3184 | 3 | 3184 | 3 | QLSP |
| Scenedesmus arcuatus var. capitatus | 1 | 0.031 | 0.001 | 16.755 | 0.526 | 3577 | 4 | 3577 | 4 | SCARCUTC |
| Scenedesmus arcuatus var. platydisca. | 2 | 0.077 | 0.002 | 25.133 | 0.669 | 4414 | 5 | 4414 | 5 | SCARCUTP |
| Scenedesmus arcuatus. | 5 | 0.135 | 0.005 | 16.755 | 0.780 | 3542 | 4 | 3542 | 4 | SCARCUTP |
| Scenedesmus armatus | 4 | 0.124 | 0.003 | 33.510 | 0.548 | 3077 | 2 | 3077 | 2 | SCARMATU |
| Scenedesmus armatus var. bogladiensis | 17 | 0.309 | 0.015 | 16.755 | 3.279 | 4406 | 5 | 4631 | 6 | SCARMATV |
| Scenedesmus armatus var. chodatii | 1 | 0.019 | 0.002 | 10.472 | 0.818 | 2883 | 2 | 2883 | 2 | SCARMAVC |
| Scenedesmus bicellularis. | 312 | 0.062 | 0.002 | 33.510 | 1.058 | 4482 | 5 | 4482 | 5 | SCBICAUD |
| Scenedesmus bijuga var. alternans | 1 | 0.031 | 0.002 | 16.755 | 0.917 | 3184 | 3 | 3184 | 3 | SCBIJUVA |
| Scenedesmus brevispina. | 1 | 0.015 | 0.001 | 8.378 | 0.456 | 2912 | 2 | 2912 | 2 | SCBBREVIS |
| Scenedesmus denticulatus var. linearis. | 5 | 0.185 | 0.005 | 50.265 | 1.090 | 3656 | 4 | 3656 | 4 | SCDENTVL |
| Scenedesmus denticulatus. | 1 | 0.008 | 0.000 | 4.189 | 0.122 | 4397 | 5 | 4397 | 5 | SCDENTIC |
| Scenedesmus dimorphus | 2 | 0.023 | 0.001 | 8.378 | 0.182 | 2601 | 1 | 3374 | 3 | SCDIHOMP |
| Scenedesmus quadricauda | 7 | 0.216 | 0.006 | 37.699 | 1.190 | 4482 | 5 | 4482 | 5 | SCQUADRI |
| Scenedesmus quadricauda var. longispina | 3 | 0.019 | 0.002 | 8.378 | 0.504 | 2872 | 2 | 2872 | 2 | SCQUADVL |
| Scenedesmus serratus. | 3 | 0.046 | 0.002 | 8.378 | 0.468 | 3195 | 3 | 3195 | 3 | SCSERBAT |
| Scenedesmus sp. | 10 | 0.116 | 0.012 | 8.378 | 3.279 | 3548 | 4 | 4635 | 6 | SCSP |
| Scenedesmus spinosus. | 3 | 0.058 | 0.002 | 16.755 | 0.928 | 2847 | 1 | 2847 | 1 | SCSPINOS |
| Scenedesmus spp. | 5 | 0.116 | 0.006 | 16.755 | 1.402 | 4367 | 5 | 3635 | 9 | SCSP |
| Scenedesmus tetrademiformis. | 1 | 0.015 | 0.001 | 8.378 | 0.462 | 2843 | 1 | 2843 | 1 | SCETRAD |
| Schroederia setigera. | 3 | 0.019 | 0.001 | 4.189 | 0.232 | 2810 | 1 | 2847 | 1 | SHSETIGR |
| Selenastrium sp. | 1 | 0.023 | 0.001 | 12.566 | 0.272 | 3656 | 4 | 3656 | 4 | SRSP |
| Sphaerocystis Schroeteri. | 1 | 0.031 | 0.003 | 16.755 | 1.646 | 3626 | 4 | 3626 | 4 | SPSCHROE |
| Staurastrum paradoxum | 14 | 0.062 | 0.003 | 4.189 | 0.242 | 4511 | 7 | 3584 | 5 | SRPARADO |
| Staurastrum sp. | 1 | 0.004 | 0.000 | 2.094 | 0.099 | 4545 | 5 | 4545 | 5 | SRSP |
| Tetraedron caudatum | 13 | 0.070 | 0.004 | 4.189 | 0.274 | 2884 | 2 | 2925 | 2 | TECAUDAT |
| Tetraedron minus. | 50 | 0.113 | 0.017 | 12.566 | 0.775 | 3202 | 3 | 3202 | 3 | TEMININU |
| Tetraedron spp. | 5 | 0.019 | 0.001 | 2.094 | 0.158 | 2929 | 2 | 2929 | 2 | TESP |
| Tetraedron spp. | 1 | 0.008 | 0.001 | 4.189 | 0.287 | 2967 | 2 | 2967 | 2 | TESPP |
| Tetrastrum glabrum. | 1 | 0.015 | 0.001 | 8.378 | 0.522 | 3201 | 3 | 3201 | 3 | TGGLABRU |
| Tribonema ambiquum. | 1 | 0.100 | 0.002 | 54.454 | 1.323 | 3080 | 2 | 3080 | 2 | TBAMBICU |
| Tribonema subtilissimum | 29 | 2.002 | 0.098 | 201.062 | 7.773 | 3434 | 3 | 3434 | 3 | TBSUBTIL |
| Ulothrix sp. #1 | 2 | 0.201 | 0.008 | 60.737 | 2.257 | 2881 | 2 | 2887 | 2 | ULSPECOA |

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide P# | max % pop. slide P# | taxon code |
|---|------------------|-----------------------------|-----------------------------|-------------------------|------------------------|---------------|
| Ulothrix spp. | 4 | 0.193 | 33.510 | 2944 | 2918 | ULSP |
| Ulothrix subtilissima | 2 | 0.247 | 87.965 | 2956 | 2956 | ULSPP |
| Ulothrix subtilissima | 1 | 0.054 | 29.322 | 2642 | 2642 | ULSUBTIL |
| Undetermined green colonies | 39 | 3.373 | 238.761 | 4367 | 3500 | GCSP |
| Undetermined green colony sp. #17 | 90 | 8.362 | 1078.613 | 3066 | 3066 | GCSP |
| Undetermined green filament | 2 | 0.093 | 25.133 | 2720 | 2720 | GCSP |
| Undetermined green filament | 5 | 0.641 | 226.195 | 3342 | 3342 | GCSP |
| Undetermined green filament #5 | 98 | 40.133 | 5696.750 | 3647 | 3647 | GCSP |
| Undetermined green filament #6 | 2 | 0.402 | 165.457 | 2647 | 2647 | GCSP |
| Undetermined green filaments | 3 | 0.185 | 62.832 | 3034 | 3034 | GCSP |
| Undetermined green individual | 268 | 6.418 | 240.855 | 3533 | 3533 | GCOC |
| Westella botryoides ? | 2 | 0.081 | 41.888 | 2884 | 2884 | WEBOTRYQ |
| total green (114 categories) | | 203.625 | 11.684 | | | |
| Achnanthes affinis. | 15 | 0.189 | 58.643 | 3143 | 3143 | ACAPPINI |
| Achnanthes biasolettiana. | 1 | 0.004 | 2.094 | 2794 | 2794 | ACBIASOL |
| Achnanthes clevei | 14 | 0.070 | 6.283 | 4601 | 4601 | ACCLEVEI |
| Achnanthes clevei var. rostrata | 9 | 0.051 | 8.727 | 2828 | 2828 | ACCLEVVR |
| Achnanthes conspicua var. brevistriata. | 1 | 0.004 | 2.094 | 4391 | 4391 | ACCONSVB |
| Achnanthes conspicua. | 3 | 0.012 | 2.094 | 2672 | 2672 | ACCONSPI |
| Achnanthes exigua | 8 | 0.031 | 2.094 | 2769 | 3246 | ACEXIGUA |
| Achnanthes flexella | 1 | 0.008 | 4.189 | 2785 | 2785 | ACFLEXEL |
| Achnanthes lanceolata | 2 | 0.008 | 2.094 | 2785 | 4601 | ACLANCEO |
| Achnanthes lanceolata var. dubia. | 4 | 0.015 | 2.094 | 2601 | 4635 | ACLANCEO |
| Achnanthes lanceolata var. elliptica. | 2 | 0.008 | 2.094 | 2872 | 2956 | ACLANCEO |
| Achnanthes laterostrata | 2 | 0.008 | 2.094 | 2841 | 4385 | ACLATERO |
| Achnanthes linearis | 1 | 0.004 | 2.094 | 3530 | 3530 | ACLINBAR |
| Achnanthes minutissima | 3 | 0.019 | 6.283 | 2887 | 2887 | ACMICROC |
| Achnanthes minutissima var. cryptocephala | 22 | 0.213 | 31.416 | 3143 | 3143 | ACHINOVIC |
| Achnanthes pinna. | 84 | 0.956 | 52.360 | 3143 | 3143 | ACHINUTI |
| Achnanthes pinna. | 3 | 0.015 | 4.189 | 2834 | 2834 | ACPINNAT |
| Achnanthes sp. #1 | 5 | 0.019 | 2.094 | 2601 | 3530 | ACSPCOA |
| Achnanthes sp. #10 | 2 | 0.008 | 2.094 | 2794 | 2853 | ACSPCOJ |
| Achnanthes sp. #23 | 1 | 0.004 | 2.094 | 2794 | 2794 | ACSPECOW |
| Achnanthes sp. #4 | 1 | 0.004 | 2.094 | 4385 | 4385 | ACSPECOD |
| Achnanthes sp. #6 | 3 | 0.015 | 4.189 | 2977 | 3263 | ACSPECOF |
| Achnanthes spp. | 45 | 0.238 | 17.453 | 2820 | 2820 | ACSP |
| Achnanthes spp. | 99 | 2.079 | 242.950 | 3143 | 3143 | ACSP |
| Amphipleura pellucida | 19 | 0.232 | 79.587 | 4482 | 4482 | APPELLUC |
| Amphora calueticia. | 1 | 0.008 | 4.189 | 3376 | 3376 | ANCALUNE |
| Amphora ovalis var. affinis auxospore | 1 | 0.016 | 8.727 | 2831 | 2831 | AMOAAUX |
| Amphora ovalis var. constricta. | 1 | 0.004 | 2.094 | 3126 | 3126 | AMOVALVC |
| Amphora ovalis var. gracilis. | 15 | 0.077 | 8.378 | 2647 | 3610 | AMOVALVG |
| Amphora ovalis var. libyca. | 2 | 0.008 | 2.094 | 3311 | 3012 | AMOVALVL |
| Amphora ovalis var. pediculus | 41 | 0.294 | 20.944 | 2814 | 4601 | AMOVALVP |
| Amphora ovalis. | 3 | 0.012 | 2.094 | 3219 | 2777 | AMOVALIS |
| Amphora perpusilla. | 43 | 0.310 | 18.850 | 3143 | 3143 | AMPERPUS |
| Amphora sp. | 14 | 0.054 | 2.094 | 2704 | 4571 | AMSP |
| Amphora sp. #3 | 1 | 0.004 | 2.094 | 4481 | 4481 | ANSPCOC |
| Amphora spp. | 4 | 0.035 | 6.283 | 2647 | 2807 | AMSP |
| Amphora veneta var. capitata. | 1 | 0.004 | 2.094 | 3582 | 3582 | AMVNEVC |
| Asterionella forosa. | 406 | 27.877 | 726.754 | 2601 | 3823 | ASFORNOS |
| Caloneis bacillum | 1 | 0.004 | 2.094 | 2803 | 2803 | CABACILL |
| Cocconeis diminuta. | 1 | 0.004 | 2.094 | 2601 | 2601 | CODIMINU |
| Cocconeis pediculus | 2 | 0.008 | 2.094 | 2647 | 2647 | COPEDICU |
| Cocconeis placentula var. euglypta. | 9 | 0.035 | 2.094 | 3143 | 2629 | COPPLACVE |

| | | | | | | | | | |
|--------------------------------------|-----|---------|-------|----------|--------|------|------|---|-----------|
| Cocconeis sp. #2 | 2 | 0.008 | 0.000 | 2.094 | 0.078 | 3713 | 4601 | 5 | COSP |
| Cocconeis sp. #2 | 6 | 0.023 | 0.001 | 2.094 | 0.232 | 2786 | 3610 | 4 | COSPECOB |
| Coccinodiscus subsalsus | 4 | 0.019 | 0.004 | 4.189 | 1.163 | 4625 | 4564 | 8 | CSSSALSA |
| Cyclotella atomus | 5 | 0.120 | 0.021 | 29.322 | 5.224 | 2672 | 2672 | 1 | CYCATORUS |
| Cyclotella comensis | 435 | 101.248 | 4.348 | 1776.046 | 55.424 | 4432 | 2672 | 5 | CYCOTENS |
| Cyclotella comensis auxospore | 12 | 0.054 | 0.002 | 4.189 | 0.268 | 3169 | 3169 | 3 | CYCMAUTO |
| Cyclotella costa auxospore | 4 | 0.027 | 0.001 | 6.283 | 0.329 | 2896 | 2896 | 2 | CYCMAUTO |
| Cyclotella costa | 167 | 3.138 | 0.129 | 119.380 | 3.055 | 3582 | 3582 | 4 | CYCMAUTO |
| Cyclotella cryptica | 1 | 0.008 | 0.000 | 4.189 | 0.102 | 3080 | 3080 | 2 | CYCMAUTO |
| Cyclotella kutzingiana | 23 | 0.164 | 0.010 | 17.453 | 1.053 | 2823 | 2823 | 1 | CYCMAUTO |
| Cyclotella meneghiniana | 11 | 0.089 | 0.008 | 14.661 | 1.538 | 3080 | 2823 | 1 | CYCMAUTO |
| Cyclotella michiganiana | 63 | 1.090 | 0.073 | 121.475 | 9.960 | 3162 | 3162 | 3 | CYCMAUTO |
| Cyclotella ocellata | 239 | 1.875 | 0.171 | 46.077 | 1.860 | 3740 | 3740 | 8 | CYCMAUTO |
| Cyclotella ocellata auxospore | 1 | 0.004 | 0.000 | 2.094 | 0.045 | 4406 | 4406 | 5 | CYCMAUTO |
| Cyclotella operculata | 2 | 0.008 | 0.000 | 2.094 | 0.074 | 3072 | 3072 | 2 | CYCMAUTO |
| Cyclotella pseudostelligera | 53 | 1.179 | 0.069 | 236.666 | 5.882 | 3072 | 3072 | 2 | CYCMAUTO |
| Cyclotella sp. #2 | 1 | 0.012 | 0.001 | 6.283 | 0.630 | 3108 | 3108 | 6 | CYCMAUTO |
| Cyclotella sp. #3 | 1 | 0.019 | 0.001 | 10.472 | 0.537 | 4394 | 4394 | 5 | CYCMAUTO |
| Cyclotella sp. #5 | 2 | 0.085 | 0.009 | 23.038 | 3.090 | 2862 | 2862 | 2 | CYCMAUTO |
| Cyclotella sp. #6 | 370 | 39.340 | 2.377 | 758.170 | 45.098 | 3199 | 3199 | 3 | CYCMAUTO |
| Cyclotella sp. auxospore | 51 | 0.336 | 0.019 | 14.661 | 1.186 | 3216 | 3216 | 3 | CYCMAUTO |
| Cyclotella sp. auxospore | 5 | 0.046 | 0.002 | 16.755 | 0.592 | 3143 | 3143 | 3 | CYCMAUTO |
| Cyclotella sp. | 30 | 0.116 | 0.013 | 2.094 | 0.820 | 2601 | 2601 | 1 | CYCMAUTO |
| Cyclotella sp. | 23 | 0.379 | 0.031 | 33.510 | 2.329 | 3377 | 3377 | 3 | CYCMAUTO |
| Cyclotella stelligera | 537 | 103.421 | 7.933 | 1380.205 | 56.761 | 3404 | 3404 | 6 | CYCMAUTO |
| Cyclotella stelligera auxospore | 1 | 0.004 | 0.000 | 2.094 | 0.099 | 2884 | 2884 | 2 | CYCMAUTO |
| Cynatopleura solea | 4 | 0.015 | 0.000 | 2.094 | 0.097 | 2647 | 2647 | 1 | CYCMAUTO |
| Cyabellia cesati | 1 | 0.004 | 0.000 | 2.094 | 0.073 | 4368 | 4368 | 5 | CYCMAUTO |
| Cyabellia cistula | 3 | 0.012 | 0.001 | 2.094 | 0.129 | 2785 | 2785 | 1 | CYCMAUTO |
| Cyabellia delicatula | 1 | 0.008 | 0.000 | 4.189 | 0.237 | 2851 | 2851 | 1 | CYCMAUTO |
| Cyabellia laevis | 1 | 0.004 | 0.000 | 2.094 | 0.110 | 2896 | 2896 | 2 | CYCMAUTO |
| Cyabellia laevis ? | 1 | 0.029 | 0.000 | 2.094 | 0.096 | 2948 | 2948 | 2 | CYCMAUTO |
| Cyabellia microcephala | 86 | 1.029 | 0.051 | 64.926 | 4.092 | 3143 | 3143 | 3 | CYCMAUTO |
| Cyabellia minuta | 7 | 0.027 | 0.001 | 2.094 | 0.142 | 2647 | 2647 | 1 | CYCMAUTO |
| Cyabellia minuta var. silesiaca | 20 | 0.104 | 0.006 | 6.283 | 0.450 | 3699 | 3699 | 7 | CYCMAUTO |
| Cyabellia prostrata var. auerswaldii | 2 | 0.054 | 0.002 | 25.133 | 0.888 | 3143 | 3143 | 3 | CYCMAUTO |
| Cyabellia sinuata | 1 | 0.004 | 0.000 | 2.094 | 0.042 | 3776 | 3776 | 4 | CYCMAUTO |
| Cyabellia sp. #13 | 1 | 0.004 | 0.000 | 2.094 | 0.072 | 2785 | 2785 | 1 | CYCMAUTO |
| Cyabellia sp. #21 | 2 | 0.008 | 0.000 | 2.094 | 0.154 | 3157 | 3157 | 3 | CYCMAUTO |
| Cyabellia sp. | 13 | 0.058 | 0.004 | 4.189 | 0.476 | 3611 | 3611 | 4 | CYCMAUTO |
| Cyabellia spp. | 4 | 0.035 | 0.001 | 6.283 | 0.231 | 3079 | 3079 | 2 | CYCMAUTO |
| Denticula tenuis var. crassula | 58 | 0.457 | 0.024 | 46.077 | 1.786 | 3143 | 3143 | 3 | CYCMAUTO |
| Denticula tenuis | 1 | 0.004 | 0.000 | 2.094 | 0.195 | 2962 | 2962 | 9 | CYCMAUTO |
| Diatoma ehrenbergii | 2 | 0.008 | 0.000 | 2.094 | 0.089 | 2601 | 2601 | 1 | CYCMAUTO |
| Diatoma spp. | 61 | 0.116 | 0.007 | 62.832 | 3.619 | 2871 | 2871 | 2 | CYCMAUTO |
| Diatoma tenue | 190 | 0.869 | 0.043 | 64.926 | 2.273 | 2785 | 2785 | 1 | CYCMAUTO |
| Diatoma tenue var. elongatum | 1 | 0.701 | 0.473 | 217.817 | 25.000 | 2601 | 2601 | 1 | CYCMAUTO |
| Diploneis oculata | 1 | 0.004 | 0.000 | 2.094 | 0.061 | 4411 | 4411 | 5 | CYCMAUTO |
| Eutomonis ornata | 3 | 0.012 | 0.001 | 2.094 | 0.137 | 2799 | 2799 | 2 | CYCMAUTO |
| Eucocconeis flexella | 1 | 0.004 | 0.000 | 2.094 | 0.137 | 2925 | 2925 | 2 | CYCMAUTO |
| Eucocconeis lapponica var. ninctei | 1 | 0.004 | 0.000 | 2.094 | 0.082 | 2841 | 2841 | 1 | CYCMAUTO |
| Eunotia curvata | 2 | 0.019 | 0.001 | 6.283 | 0.243 | 3434 | 3434 | 3 | CYCMAUTO |
| Eunotia sp. | 3 | 0.012 | 0.000 | 4.189 | 0.168 | 3532 | 3532 | 4 | CYCMAUTO |
| Pragilaria brevistriata | 1 | 0.008 | 0.000 | 4.189 | 0.166 | 2794 | 2794 | 1 | CYCMAUTO |
| Pragilaria brevistriata var. inflata | 1 | 0.004 | 0.000 | 2.094 | 0.138 | 3406 | 3406 | 6 | CYCMAUTO |
| Pragilaria capucina | 48 | 4.417 | 0.233 | 284.837 | 11.945 | 3034 | 3034 | 7 | CYCMAUTO |
| Pragilaria construens | 6 | 0.124 | 0.006 | 41.888 | 1.934 | 2702 | 2702 | 1 | CYCMAUTO |
| Pragilaria construens var. minuta | 88 | 0.873 | 0.074 | 41.888 | 2.281 | 2647 | 2647 | 1 | CYCMAUTO |
| Pragilaria construens var. pumila | 1 | 0.319 | 0.000 | 10.472 | 0.229 | 2647 | 2647 | 1 | CYCMAUTO |
| Pragilaria construens var. venter | 5 | 0.031 | 0.002 | 6.283 | 0.346 | 2843 | 2843 | 1 | CYCMAUTO |

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|--|---------|-------|----------|--------|------|---|------|---|-----------|
| <i>Fragilaria construens</i> var. ? | 0.363 | 0.043 | 27.227 | 2.273 | 3374 | 3 | 4519 | 7 | PRCONSVQ |
| <i>Fragilaria crotonensis</i> | 119.271 | 5.841 | 1466.076 | 46.591 | 2814 | 1 | 2820 | 1 | PRCHOTOM |
| <i>Fragilaria intermedia</i> | 0.081 | 0.007 | 12.566 | 1.395 | 3711 | 4 | 3711 | 4 | PRINTERM |
| <i>Fragilaria intermedia</i> var. <i>fallax</i> | 4.546 | 0.303 | 203.156 | 12.658 | 2769 | 1 | 3005 | 7 | PRINTEVP |
| <i>Fragilaria leptostauron</i> | 0.058 | 0.002 | 10.472 | 0.279 | 2649 | 1 | 2649 | 1 | PRLEPTOS |
| <i>Fragilaria leptostauron</i> var. <i>dubia</i> | 0.008 | 0.000 | 4.189 | 0.182 | 2800 | 1 | 2800 | 1 | PRLEPTVD |
| <i>Fragilaria pantocsekii</i> var. <i>binodis</i> | 0.012 | 0.000 | 6.283 | 0.262 | 2838 | 1 | 2838 | 1 | PRPANTVB |
| <i>Fragilaria pinnata</i> var. <i>intercedens</i> | 0.023 | 0.001 | 6.283 | 0.235 | 4601 | 5 | 4601 | 5 | PRPINNVI |
| <i>Fragilaria pinnata</i> var. <i>lanceolata</i> | 0.077 | 0.002 | 14.661 | 0.240 | 3077 | 2 | 3077 | 2 | PRPINNVL |
| <i>Fragilaria pinnata</i> | 3.455 | 0.118 | 314.159 | 11.728 | 4601 | 5 | 4601 | 5 | PRPINNAT |
| <i>Fragilaria</i> sp. #9 | 0.004 | 0.000 | 2.094 | 0.110 | 2896 | 2 | 2896 | 2 | PRSPCOI |
| <i>Fragilaria</i> sp. | 0.108 | 0.009 | 4.189 | 0.685 | 4415 | 5 | 3638 | 9 | PRSP |
| <i>Fragilaria</i> spp. | 0.537 | 0.017 | 117.286 | 2.606 | 3077 | 2 | 3192 | 3 | PRSP |
| <i>Fragilaria vaucheriae</i> | 0.054 | 0.002 | 16.755 | 0.446 | 2649 | 1 | 2649 | 1 | PRVAUCHE |
| <i>Fragilaria vaucheriae</i> var. <i>capitellata</i> | 0.402 | 0.024 | 108.908 | 8.100 | 2965 | 9 | 2965 | 9 | PRVAUCVC |
| <i>Fragilaria vaucheriae</i> var. <i>lanceolata</i> | 0.015 | 0.001 | 4.189 | 0.245 | 2918 | 2 | 2918 | 2 | PRVAUCVL |
| <i>Fragilaria vaucheriae</i> var. <i>truncata</i> | 0.008 | 0.000 | 2.094 | 0.106 | 2647 | 1 | 2780 | 1 | PRVAUCVT |
| <i>Gomphonema gracile</i> | 0.004 | 0.000 | 2.094 | 0.049 | 3079 | 2 | 3079 | 2 | GOGRACIL |
| <i>Gomphonema intricatum</i> | 0.008 | 0.000 | 2.094 | 0.091 | 2785 | 1 | 3374 | 3 | GOLNTRIC |
| <i>Gomphonema intricatum</i> var. <i>pumila</i> | 0.027 | 0.001 | 4.189 | 0.256 | 4601 | 5 | 3530 | 4 | GOLNTRVP |
| <i>Gomphonema olivaceum</i> | 0.004 | 0.000 | 2.094 | 0.098 | 2749 | 1 | 2749 | 1 | GOLIVAC |
| <i>Gomphonema parvulum</i> | 0.004 | 0.000 | 2.094 | 0.099 | 2884 | 2 | 2884 | 2 | GOPARVUL |
| <i>Gomphonema</i> sp. | 0.027 | 0.001 | 2.094 | 0.140 | 2649 | 1 | 3172 | 3 | GOSP |
| <i>Gomphonema</i> spp. | 0.043 | 0.001 | 8.378 | 0.313 | 4601 | 5 | 4601 | 5 | GOSPP |
| <i>Gyrosigma sciotosense</i> | 0.012 | 0.000 | 2.094 | 0.078 | 4409 | 5 | 4601 | 5 | GYSCIOTE |
| <i>Hannaea arcus</i> | 0.004 | 0.000 | 2.094 | 0.147 | 2903 | 2 | 2903 | 2 | HNAARCUS |
| <i>Hantzschia amphioxys</i> | 0.004 | 0.000 | 2.094 | 0.129 | 3202 | 3 | 3202 | 3 | HNAAPHIO |
| <i>Melosira distans</i> var. <i>alpigena</i> | 0.039 | 0.003 | 12.566 | 1.091 | 4698 | 5 | 2685 | 8 | MEDISTVA |
| <i>Melosira granulata</i> alpha status | 0.019 | 0.001 | 10.472 | 0.548 | 4625 | 6 | 4625 | 6 | MEGRANVS |
| <i>Melosira granulata</i> | 0.008 | 0.001 | 4.189 | 0.673 | 3064 | 8 | 3064 | 8 | MEGRANUL |
| <i>Melosira islandica</i> | 20.336 | 1.766 | 592.713 | 25.157 | 2647 | 1 | 3298 | 7 | MEISLAND |
| <i>Melosira italica</i> subsp. <i>subarctica</i> | 33.716 | 5.175 | 362.330 | 10.364 | 3342 | 8 | 4563 | 8 | MEITALIC |
| <i>Melosira italica</i> var. <i>tenuis</i> | 4.397 | 0.549 | 58.643 | 6.113 | 3406 | 6 | 3412 | 6 | MEITALVT |
| <i>Melosira</i> sp. autospore. | 0.008 | 0.000 | 2.094 | 0.113 | 2769 | 9 | 2771 | 9 | MEALXOSP |
| <i>Melosira</i> sp. | 0.062 | 0.004 | 33.510 | 2.254 | 2958 | 2 | 2958 | 2 | MESP |
| <i>Navicula anlica</i> var. <i>signata</i> | 0.015 | 0.001 | 4.189 | 0.476 | 3713 | 4 | 3755 | 8 | NAANGLVS |
| <i>Navicula anlica</i> | 0.015 | 0.001 | 2.094 | 0.151 | 2803 | 1 | 3778 | 4 | NAANGLIC |
| <i>Navicula aurora</i> | 0.004 | 0.000 | 2.094 | 0.061 | 4397 | 5 | 4397 | 5 | NAAURORA |
| <i>Navicula bacillum</i> | 0.012 | 0.001 | 2.094 | 0.151 | 2841 | 1 | 3778 | 4 | NABACILL |
| <i>Navicula capitata</i> | 0.046 | 0.002 | 8.378 | 0.313 | 4601 | 5 | 4601 | 5 | NACAPITA |
| <i>Navicula capitata</i> var. <i>lunenburgensis</i> | 0.015 | 0.000 | 2.094 | 0.091 | 2744 | 1 | 3374 | 3 | NACAPITL |
| <i>Navicula cryptocephala</i> var. <i>intermedia</i> | 0.015 | 0.001 | 4.189 | 0.237 | 2851 | 1 | 2851 | 1 | NACRYPVI |
| <i>Navicula cryptocephala</i> var. <i>veneta</i> | 0.035 | 0.001 | 4.189 | 0.237 | 4409 | 5 | 2851 | 1 | NACRYPVV |
| <i>Navicula decussis</i> | 0.019 | 0.001 | 2.094 | 0.107 | 2601 | 1 | 3376 | 3 | NACRYPTO |
| <i>Navicula diluviana</i> | 0.004 | 0.000 | 2.094 | 0.107 | 2869 | 2 | 2869 | 2 | NADECUSS |
| <i>Navicula fracta</i> | 0.004 | 0.000 | 2.094 | 0.097 | 2702 | 1 | 2702 | 1 | NADILUVI |
| <i>Navicula gastrum</i> var. <i>signata</i> | 0.008 | 0.000 | 2.094 | 0.256 | 3530 | 4 | 2649 | 1 | NAPRACTA |
| <i>Navicula lanceolata</i> | 0.015 | 0.000 | 2.094 | 0.056 | 2649 | 1 | 2649 | 1 | NAGASTVS |
| <i>Navicula lanceolata</i> var. <i>signata</i> | 0.004 | 0.000 | 2.094 | 0.123 | 2915 | 2 | 2915 | 2 | NALPORT |
| <i>Navicula latens</i> | 0.015 | 0.001 | 4.189 | 0.219 | 2881 | 2 | 2896 | 2 | NALANCEO |
| <i>Navicula latens</i> var. <i>upsaliensis</i> | 0.015 | 0.002 | 2.094 | 0.552 | 2702 | 1 | 3409 | 6 | NALATENS |
| <i>Navicula micropapula</i> | 0.012 | 0.000 | 2.094 | 0.103 | 2841 | 1 | 2933 | 2 | NAMENIVU |
| <i>Navicula minima</i> var. <i>okamurae</i> | 0.012 | 0.000 | 4.189 | 0.107 | 2647 | 1 | 3376 | 3 | NAMICROP |
| <i>Navicula nysseensis</i> fo. <i>minor</i> | 0.004 | 0.001 | 2.094 | 0.325 | 2724 | 7 | 2647 | 1 | NAMINIVO |
| <i>Navicula perpusilla</i> | 0.004 | 0.000 | 2.094 | 0.046 | 2647 | 1 | 2647 | 1 | NANVASPM |
| <i>Navicula pupula</i> | 0.032 | 0.001 | 2.094 | 0.351 | 3635 | 9 | 3635 | 9 | NAPERPUS |
| <i>Navicula pupula</i> var. <i>capitata</i> | 0.004 | 0.002 | 8.727 | 0.493 | 2831 | 1 | 2831 | 1 | NAPUPULA |
| <i>Navicula pupula</i> var. <i>mutata</i> | 0.012 | 0.001 | 2.094 | 0.091 | 3374 | 3 | 3374 | 3 | NAPUPUVC |
| <i>Navicula radiosa</i> var. <i>tenella</i> | 0.138 | 0.001 | 4.189 | 0.244 | 4601 | 5 | 3015 | 7 | NAPUPUVM |
| | | 0.006 | 4.189 | 0.464 | 3548 | 4 | 3610 | 4 | NARADIIVT |

| | | | | | | | | | | |
|---|-----|--------|-------|---------|--------|------|---|------|---|-----------|
| Navicula radiosa. | 2 | 0.012 | 0.000 | 4.189 | 0.162 | 3434 | 3 | 3434 | 3 | NARADIOS |
| Navicula reinhardtii. | 1 | 0.034 | 0.000 | 2.094 | 0.088 | 2803 | 1 | 2803 | 1 | NAREINHA |
| Navicula rhynchocephala | 1 | 0.004 | 0.000 | 2.094 | 0.078 | 4601 | 5 | 4601 | 5 | NARHYNCH |
| Navicula scutellonoides | 1 | 0.004 | 0.001 | 2.094 | 0.342 | 3638 | 9 | 3638 | 9 | NASCUTEL |
| Navicula sp. #23. | 1 | 0.004 | 0.000 | 2.094 | 0.049 | 3079 | 2 | 3079 | 2 | NASPECOM |
| Navicula sp. #44. | 14 | 0.178 | 0.008 | 37.699 | 1.331 | 3143 | 3 | 3143 | 3 | NASPECAR |
| Navicula sp. #8 | 1 | 0.004 | 0.000 | 2.094 | 0.046 | 2647 | 1 | 2647 | 1 | NASPECOH |
| Navicula sp. | 49 | 0.213 | 0.017 | 8.727 | 0.699 | 2816 | 1 | 2816 | 1 | NASPP |
| Navicula spp. | 30 | 0.448 | 0.017 | 35.605 | 1.257 | 3143 | 3 | 3143 | 3 | NASPP |
| Navicula subrotundata | 2 | 0.008 | 0.000 | 2.094 | 0.091 | 3374 | 3 | 3374 | 3 | NASROTUM |
| Navicula tripunctata. | 1 | 0.004 | 0.000 | 2.094 | 0.129 | 2769 | 1 | 2769 | 1 | NATRIPIUM |
| Navicula tuscua. | 1 | 0.008 | 0.000 | 4.189 | 0.211 | 2834 | 1 | 2834 | 1 | NATUSCUL |
| Navicula vanheurckii. | 1 | 0.008 | 0.000 | 4.189 | 0.241 | 2871 | 2 | 2871 | 2 | NAVANHEU |
| Nitzschia acicularioides. | 1 | 0.004 | 0.000 | 2.094 | 0.077 | 2740 | 1 | 2740 | 1 | NIACIRIO |
| Nitzschia acicularis. | 98 | 1.164 | 0.061 | 48.171 | 1.397 | 4397 | 5 | 4397 | 5 | NIACICUL |
| Nitzschia acuta | 2 | 0.008 | 0.000 | 2.094 | 0.112 | 2906 | 2 | 2906 | 2 | NIACUTA |
| Nitzschia angustata | 1 | 0.004 | 0.000 | 2.094 | 0.046 | 2647 | 1 | 2647 | 1 | NIANGUST |
| Nitzschia angustata var. acuta. | 1 | 0.008 | 0.000 | 4.189 | 0.091 | 2647 | 1 | 2647 | 1 | NIANGUVA |
| Nitzschia bacata fo. linearis | 2 | 0.015 | 0.001 | 6.283 | 0.165 | 2601 | 1 | 2754 | 1 | NIACAPFL |
| Nitzschia bacata. | 29 | 0.205 | 0.012 | 23.038 | 0.730 | 2649 | 1 | 4463 | 9 | NIACAPFL |
| Nitzschia confinis. | 102 | 0.668 | 0.091 | 23.038 | 2.410 | 3342 | 8 | 4567 | 8 | NIACAPFL |
| Nitzschia dissipata | 93 | 0.533 | 0.046 | 12.566 | 1.527 | 2780 | 1 | 2687 | 8 | NIACAPFL |
| Nitzschia filiformis. | 1 | 0.004 | 0.000 | 2.094 | 0.088 | 3311 | 3 | 3311 | 3 | NIACAPFL |
| Nitzschia fonticola | 14 | 0.081 | 0.004 | 10.472 | 0.508 | 4420 | 5 | 3346 | 8 | NIACAPFL |
| Nitzschia fonticola var. pelagica | 8 | 0.070 | 0.003 | 10.472 | 0.491 | 3143 | 3 | 2883 | 2 | NIACAPFL |
| Nitzschia frustulum var. perminuta. | 1 | 0.008 | 0.000 | 4.189 | 0.232 | 2847 | 1 | 2847 | 1 | NIACAPFL |
| Nitzschia kutingiana | 17 | 0.113 | 0.007 | 17.453 | 1.136 | 2820 | 1 | 2820 | 1 | NIACAPFL |
| Nitzschia palea | 8 | 0.046 | 0.002 | 6.283 | 0.211 | 3077 | 2 | 2834 | 1 | NIACAPFL |
| Nitzschia paleacea. | 5 | 0.035 | 0.001 | 10.472 | 0.189 | 2601 | 1 | 2601 | 1 | NIACAPFL |
| Nitzschia planctonica | 11 | 0.082 | 0.005 | 8.727 | 0.794 | 2828 | 1 | 2828 | 1 | NIACAPFL |
| Nitzschia pseudoatomus. | 1 | 0.004 | 0.000 | 2.094 | 0.099 | 2788 | 1 | 2788 | 1 | NIACAPFL |
| Nitzschia recta | 1 | 0.004 | 0.000 | 2.094 | 0.078 | 4601 | 5 | 4601 | 5 | NIACAPFL |
| Nitzschia sigmoidea | 6 | 0.035 | 0.001 | 4.189 | 0.193 | 2649 | 1 | 2702 | 1 | NIACAPFL |
| Nitzschia sp. | 114 | 0.507 | 0.046 | 20.944 | 1.143 | 2814 | 1 | 3754 | 8 | NIACAPFL |
| Nitzschia sp. #1. | 18 | 0.104 | 0.005 | 6.283 | 0.321 | 2869 | 2 | 2869 | 2 | NIACAPFL |
| Nitzschia sp. #10 | 1 | 0.012 | 0.000 | 6.283 | 0.265 | 2803 | 1 | 2803 | 1 | NIACAPFL |
| Nitzschia sp. #16 | 1 | 0.004 | 0.000 | 2.094 | 0.034 | 3077 | 2 | 3077 | 2 | NIACAPFL |
| Nitzschia sp. #18 | 1 | 0.004 | 0.000 | 2.094 | 0.074 | 3143 | 3 | 3143 | 3 | NIACAPFL |
| Nitzschia sp. #2. | 29 | 0.201 | 0.010 | 14.661 | 0.611 | 2838 | 1 | 2838 | 1 | NIACAPFL |
| Nitzschia sp. #32 | 16 | 0.081 | 0.006 | 6.283 | 0.491 | 2883 | 2 | 2883 | 2 | NIACAPFL |
| Nitzschia sp. #6. | 2 | 0.008 | 0.000 | 2.094 | 0.115 | 3115 | 2 | 3115 | 2 | NIACAPFL |
| Nitzschia sp. #7. | 8 | 0.039 | 0.002 | 4.189 | 0.303 | 3532 | 4 | 3778 | 4 | NIACAPFL |
| Nitzschia sp. #8. | 3 | 0.012 | 0.000 | 2.094 | 0.086 | 2982 | 2 | 2982 | 2 | NIACAPFL |
| Nitzschia sp. #9. | 2 | 0.008 | 0.000 | 2.094 | 0.084 | 2881 | 2 | 3532 | 4 | NIACAPFL |
| Nitzschia spiculoides | 7 | 0.043 | 0.002 | 6.283 | 0.231 | 2977 | 2 | 2843 | 1 | NIACAPFL |
| Nitzschia spp. | 93 | 1.159 | 0.075 | 29.322 | 1.905 | 3434 | 3 | 3755 | 8 | NIACAPFL |
| Nitzschia tarda | 1 | 0.004 | 0.000 | 2.094 | 0.088 | 3311 | 3 | 3311 | 3 | NIACAPFL |
| Opephora sp. | 1 | 0.004 | 0.000 | 2.094 | 0.089 | 2642 | 1 | 2642 | 1 | NIACAPFL |
| Pannularia burkii | 1 | 0.004 | 0.000 | 2.094 | 0.089 | 2642 | 1 | 2642 | 1 | NIACAPFL |
| Pannularia sp. | 1 | 0.004 | 0.000 | 2.094 | 0.089 | 2642 | 1 | 2642 | 1 | NIACAPFL |
| Rhizosolenia eriensis | 338 | 17.822 | 0.971 | 301.593 | 9.132 | 3405 | 6 | 3126 | 2 | NIACAPFL |
| Rhizosolenia gracilis | 297 | 11.128 | 0.768 | 224.103 | 7.446 | 2601 | 1 | 3018 | 2 | NIACAPFL |
| Rhoicosphenia curvata | 1 | 0.004 | 0.000 | 2.094 | 0.046 | 2647 | 1 | 2647 | 1 | NIACAPFL |
| Rhoicosphenia sp. | 1 | 0.008 | 0.000 | 4.189 | 0.085 | 3776 | 4 | 3776 | 4 | NIACAPFL |
| Skeletonema sp. | 2 | 0.197 | 0.005 | 94.248 | 2.290 | 3080 | 2 | 3080 | 2 | NIACAPFL |
| Stephanodiscus alpinus. | 41 | 0.216 | 0.017 | 8.378 | 0.687 | 3077 | 2 | 3694 | 7 | NIACAPFL |
| Stephanodiscus astraea var. #1. | 1 | 0.012 | 0.001 | 6.283 | 0.342 | 2786 | 1 | 2786 | 1 | NIACAPFL |
| Stephanodiscus binderanus | 27 | 1.352 | 0.084 | 79.583 | 12.162 | 3077 | 2 | 3245 | 9 | NIACAPFL |
| Stephanodiscus binderanus var. oestrupii. | 1 | 0.035 | 0.001 | 18.850 | 0.300 | 2601 | 1 | 2601 | 1 | NIACAPFL |
| Stephanodiscus hantzschii | 324 | 26.806 | 2.876 | 240.855 | 27.729 | 2786 | 1 | 2786 | 1 | NIACAPFL |

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide # | max % pop. slide # | taxon code |
|--|------------------|-----------------------------|-----------------------------|------------------------|-----------------------|---------------|
| Stephanodiscus minutus aurospore. | 1 | 0.004 | 0.000 | 2647 | 1 | STMIAXO |
| Stephanodiscus minutus. | 390 | 52.064 | 6.464 | 3701 | 7 | STMINUT |
| Stephanodiscus niagarae. | 27 | 0.155 | 0.009 | 3071 | 9 | STNIAGAR |
| Stephanodiscus sp. #10. | 66 | 2.147 | 0.088 | 3077 | 2 | STSPCOJ |
| Stephanodiscus sp. #13. | 1 | 0.012 | 0.001 | 2871 | 2 | STSPCOM |
| Stephanodiscus sp. #14. | 2 | 0.008 | 0.001 | 3126 | 2 | STSPCOM |
| Stephanodiscus sp. #15. | 5 | 0.043 | 0.004 | 2606 | 1 | STSPCOO |
| Stephanodiscus sp. #16. | 122 | 3.496 | 0.296 | 2828 | 1 | STSPCOO |
| Stephanodiscus sp. #5. | 47 | 0.356 | 0.026 | 2601 | 1 | STSPCOE |
| Stephanodiscus sp. #6. | 6 | 0.035 | 0.006 | 2978 | 2 | STSPCOF |
| Stephanodiscus sp. #8. | 15 | 0.070 | 0.010 | 4635 | 6 | STSPCOH |
| Stephanodiscus sp. #9. | 18 | 0.144 | 0.012 | 2817 | 1 | STSPCOI |
| Stephanodiscus sp. aurospore. | 2 | 0.015 | 0.001 | 2650 | 1 | STSPKOSP |
| Stephanodiscus sp. | 1 | 0.004 | 0.001 | 2723 | 7 | STSPKOSU |
| Stephanodiscus sp.. | 44 | 0.232 | 0.039 | 3750 | 8 | STSP |
| Stephanodiscus spp. | 52 | 1.109 | 0.074 | 2647 | 1 | STSPPP |
| Stephanodiscus subtilis. | 51 | 2.446 | 0.078 | 3080 | 2 | STSUBTIL |
| Stephanodiscus tenuis. | 29 | 1.314 | 0.042 | 2601 | 1 | STTENUIS |
| Stephanodiscus transilvanicus. | 2 | 0.008 | 0.001 | 2654 | 1 | STTRANSI |
| Surirella angusta. | 5 | 0.027 | 0.001 | 4432 | 5 | SUANGUST |
| Surirella ovata var. pinnata. | 1 | 0.004 | 0.000 | 3077 | 2 | SUOVATAP |
| Surirella sp. | 1 | 0.004 | 0.000 | 3434 | 3 | SUSP |
| Synedra delicatissima var. angustissima. | 267 | 5.810 | 0.416 | 2647 | 1 | SYDELIVA |
| Synedra demerarae. | 1 | 0.008 | 0.001 | 3247 | 9 | SYDEMER |
| Synedra filiformis. | 423 | 25.090 | 1.546 | 3811 | 6 | SYFILIFO |
| Synedra minuscula. | 11 | 0.046 | 0.002 | 2744 | 1 | SYMINUSC |
| Synedra ostenfeldii. | 186 | 2.420 | 0.184 | 3341 | 8 | SYOSTENF |
| Synedra parasitica. | 1 | 0.004 | 0.001 | 2626 | 6 | SYPARASI |
| Synedra sp. | 31 | 0.172 | 0.010 | 2830 | 1 | SYSP |
| Synedra spp.. | 19 | 0.261 | 0.014 | 2823 | 1 | SYSPPP |
| Synedra tenera. | 1 | 0.015 | 0.001 | 3121 | 2 | SYTENER |
| Synedra ulna var. chaseana. | 88 | 0.580 | 0.034 | 2814 | 1 | SYULNAVC |
| Synedra ulna. | 12 | 0.089 | 0.005 | 2601 | 1 | SYULNA |
| Tabellaria fenestrata. | 56 | 2.319 | 0.115 | 2814 | 1 | TAFENEST |
| Tabellaria fenestrata var. genticulata. | 4 | 0.039 | 0.002 | 4415 | 5 | TAPENEVG |
| Tabellaria flocculosa. | 6 | 0.247 | 0.015 | 2898 | 2 | TAPLOCU |
| Tabellaria flocculosa var. linearis. | 316 | 27.113 | 1.402 | 3077 | 2 | TAFLOCVL |
| Thalassiosira fluviatilis. | 1 | 0.004 | 0.000 | 2786 | 1 | THFLUVIA |
| Undetermined centric diatom sp. | 39 | 0.377 | 0.064 | 2814 | 1 | UDSP |
| Undetermined centric diatom spp. | 113 | 4.555 | 0.643 | 3343 | 8 | UDSPPP |
| total diatoms (262 categories) | | 687.606 | 48.604 | | | |
| Chrysococcus dokidophorus. | 119 | 2.044 | 0.122 | 4648 | 5 | CVDOKIDO |
| Chrysophycean cyst. | 245 | 4.534 | 0.286 | 2933 | 2 | CHCYST |
| Coccolid chrysophyte. | 72 | 21.102 | 1.136 | 3072 | 2 | CHCOCCOI |
| Dinobryon cyst. | 83 | 0.885 | 0.073 | 3341 | 8 | DNCYST |
| Dinobryon cysts. | 1 | 0.012 | 0.000 | 2649 | 1 | DNCYSTS |
| Dinobryon divergens. | 5 | 0.336 | 0.014 | 3072 | 2 | DNDIVERG |
| Dinobryon sp. | 37 | 1.939 | 0.103 | 2817 | 1 | DNSP |
| Dinobryon spp.. | 122 | 9.463 | 0.383 | 4394 | 5 | DNSPP |
| Mallomonas akrokomos. | 1 | 0.004 | 0.000 | 2647 | 1 | MLAKROKO |
| Mallomonas alpina. | 80 | 0.457 | 0.024 | 3365 | 3 | MLALPINA |
| Mallomonas alpina statospore. | 2 | 0.008 | 0.001 | 2877 | 2 | MLALSTAT |
| Mallomonas elongata. | 5 | 0.035 | 0.001 | 3405 | 6 | MLELONCA |

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|---|-----|--------|-------|----------|--------|------|---|------|---|----------|
| Mallomonas pseudocoronata | 71 | 0.413 | 0.021 | 10.472 | 0.493 | 3312 | 3 | 3156 | 3 | MLPSEUDO |
| Mallomonas sp. #3 | 10 | 0.039 | 0.002 | 2.094 | 0.165 | 2647 | 1 | 2754 | 1 | MLSPECOC |
| Mallomonas sp. | 5 | 0.019 | 0.001 | 2.094 | 0.150 | 2794 | 1 | 3129 | 3 | MLSP |
| Mallomonas spp. | 1 | 0.008 | 0.000 | 4.189 | 0.159 | 3121 | 2 | 3121 | 2 | MLSPP |
| Mallomonas statospore | 21 | 0.128 | 0.010 | 10.472 | 0.799 | 4345 | 5 | 4345 | 5 | MLSTATOS |
| Ochrononas sp. | 25 | 0.796 | 0.055 | 134.041 | 10.500 | 4545 | 5 | 3004 | 7 | OCSP |
| Ochrononas spp. | 388 | 48.833 | 3.058 | 1135.161 | 17.888 | 3405 | 6 | 3034 | 2 | OCSP |
| Spiniferomonas sp. | 106 | 1.269 | 0.060 | 37.699 | 3.015 | 3845 | 4 | 3845 | 4 | SPSP |
| Spiniferomonas spp. | 4 | 0.039 | 0.001 | 8.378 | 0.074 | 3023 | 2 | 3023 | 2 | SPSP |
| Tribonema sp. | 12 | 0.298 | 0.023 | 43.982 | 4.102 | 2962 | 9 | 2962 | 9 | TBSP |
| Tribonema spp. | 1 | 0.008 | 0.000 | 4.189 | 0.264 | 3271 | 3 | 3271 | 3 | TBSP |
| Undetermined colonial chrysophyte | 5 | 0.533 | 0.105 | 111.003 | 20.000 | 3407 | 6 | 3410 | 6 | UNCOLOCH |
| Uroglana sp. | 1 | 0.541 | 0.028 | 293.215 | 14.941 | 2650 | 1 | 2650 | 1 | UOSP |
| Uroglana volvox | 2 | 0.325 | 0.040 | 104.720 | 18.450 | 3299 | 7 | 3299 | 7 | UOVOLVOX |
| Uroglanopsis americana. | 8 | 1.229 | 0.047 | 184.307 | 7.291 | 3564 | 4 | 3564 | 4 | URAHERIC |
| total chrysophytes { 27 categories} | | 95.294 | 5.594 | | | | | | | |

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide P# | max % pop. slide P# | taxon code |
|--|---------------|--------------------------|--------------------------|----------------------|---------------------|------------|
| Cryptomonas erosa | 20 | 0.135 | 14.661 | 1.351 | 2601 | 1 |
| Cryptomonas ovata | 358 | 6.472 | 50.265 | 5.464 | 4530 | 5 |
| Cryptomonas sp. | 5 | 0.035 | 0.002 | 0.267 | 4624 | 5 |
| Cryptomonas spp. | 5 | 0.158 | 23.038 | 1.664 | 3776 | 4 |
| Rhodomonas minuta | 252 | 9.677 | 247.138 | 13.068 | 3356 | 3 |
| Rhodomonas minuta var. nannoplantica | 474 | 49.274 | 498.466 | 19.931 | 3039 | 2 |
| total cryptomonads { 6 categories} | | 65.751 | | | | |

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|---------------------------------|-----|-------|--------|-------|------|---|------|---|----------|
| Amphidinium luteum. | 15 | 0.081 | 6.283 | 0.411 | 2892 | 2 | 2925 | 2 | AILUTEUM |
| Amphidinium sp. | 10 | 0.058 | 10.472 | 0.226 | 3077 | 2 | 3008 | 7 | AISP |
| Ceratium hirundinella | 61 | 0.309 | 12.566 | 2.239 | 3689 | 7 | 3689 | 7 | CRHIRUND |
| Gyanodinium eurytopum | 3 | 0.012 | 2.094 | 0.123 | 2881 | 2 | 2918 | 2 | GJEURYTO |
| Gyanodinium excavatum | 1 | 0.004 | 2.094 | 0.214 | 2654 | 1 | 2654 | 1 | GJEXCAVA |
| Gyanodinium lacustre. | 1 | 0.004 | 2.094 | 0.069 | 2881 | 2 | 2881 | 2 | GJLACUST |
| Gyanodinium lantzschii. | 2 | 0.012 | 4.189 | 0.299 | 3129 | 3 | 3129 | 3 | GJLANTZS |
| Gyanodinium latum | 23 | 0.124 | 8.378 | 0.980 | 3292 | 7 | 4561 | 8 | GJLATUM |
| Gyanodinium obesum. | 1 | 0.004 | 2.094 | 0.089 | 2642 | 1 | 2642 | 1 | GJOBESUM |
| Gyanodinium ordinatum | 211 | 1.920 | 35.605 | 3.922 | 3342 | 8 | 4561 | 8 | GJORDINA |
| Gyanodinium purpureum | 12 | 0.058 | 6.283 | 0.475 | 2929 | 2 | 2929 | 2 | GJPURPUR |
| Gyanodinium sinile. | 1 | 0.008 | 4.189 | 0.178 | 2642 | 1 | 2642 | 1 | GJSINILE |

| | | | | | | | |
|--|-------|-------|--------|-------|------|---|----------|
| Gymnodinium sp. | 0.058 | 0.003 | 12.566 | 0.606 | 2936 | 2 | GYMNODIN |
| Gymnodinium sp. | 0.287 | 0.027 | 8.727 | 2.222 | 2828 | 1 | GJSP |
| Gymnodinium spp. | 0.479 | 0.026 | 14.661 | 1.111 | 3312 | 3 | GJSP |
| Gymnodinium triceratium | 0.035 | 0.002 | 4.189 | 0.289 | 2689 | 1 | GJTRICER |
| Peridinium inconspicuum ? | 0.004 | 0.000 | 2.094 | 0.038 | 2601 | 1 | PEINCOMQ |
| Peridinium spp. | 0.043 | 0.003 | 6.283 | 0.427 | 2912 | 2 | PESP |
| Peridinium spp. | 0.012 | 0.000 | 6.283 | 0.259 | 3312 | 3 | PESP |
| Peridinium willeyi | 0.004 | 0.000 | 2.094 | 0.129 | 3836 | 4 | PEWILLEI |
| Unidentified dinoflagellate sp. | 0.070 | 0.006 | 20.944 | 0.839 | 3532 | 4 | DPSP |
| Unidentified dinoflagellate spp. | 0.031 | 0.004 | 4.189 | 1.515 | 2704 | 1 | DPSP |
| total dinoflagellates (22 categories) | 3.613 | 0.269 | | | | | |

| name | number slides | average density & % pop. | maximum density & % pop. | max density slide P# | max % pop. slide P# | taxon code |
|---|------------------|-----------------------------|-----------------------------|-------------------------|------------------------|---------------|
| Beqgiatoa alba. { 1 categories) | 12 | 2.025 | 219.911 | 4628 | 6 | BEALBA |
| total bacteria | | 2.025 | 45.714 | | | |

```

* * * * *
total number of slides: 542
minimum total density: 8.38
average total density: 1642.96
* * * * *
minimum at: 3243
maximum at: 3405

```

